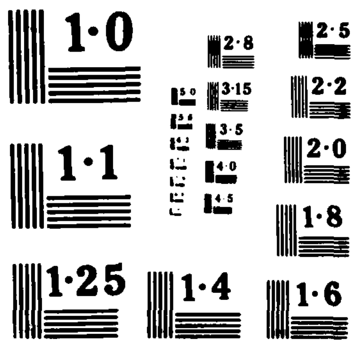
AD-A183 012 SIMPLE ANALYTICAL METHODS FOR ESTIMATING SHORT-TERM RAINFALL(U) ARMY ENGINEER TOPOGRAPHIC LABS FORT BELVOIR VA R L WEXLER NOV 86 ETL-0441 1/1

UNCLASSIFIED F/G 4/2 NL


1.0
2.8
2.5
3.15
2.2
5.0
3.5
2.0
1.1
4.0
4.5
1.8
1.25
1.4
1.6

ETL-0441

DTIC FILE COPY

AD-A183 812

Simple analytical methods for estimating short-term rainfall

Ruth L. Wexler

November 1986

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION IS UNLIMITED

Prepared for
U.S. ARMY CORPS OF ENGINEERS
ENGINEER TOPOGRAPHIC LABORATORIES
FORT BELVOIR, VIRGINIA 22060-5546

87 8 015

E T L

U.S. ARMY ENGINEER TOPOGRAPHIC LABORATORIES
ETL

UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE

AD-A183812

REPORT DOCUMENTATION PAGE

Form Approved
OMB No 0704-0188
Exp Date Jun 30, 1986

1a. REPORT SECURITY CLASSIFICATION: Unclassified	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT: Approved for public release; distribution is unlimited.
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S): ETL-0441	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION: U.S. Army Engineer Topographic Laboratories — 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION
6c. ADDRESS (City, State, and ZIP Code): Fort Belvoir, VA 22060-5546	7b. ADDRESS (City, State, and ZIP Code)
8a. NAME OF FUNDING/SPONSORING ORGANIZATION: U.S. Army Engineer Topographic Laboratories — 8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c. ADDRESS (City, State, and ZIP Code): Fort Belvoir, VA 22060-5546	10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO	WORK UNIT ACCESSION NO
	QG652C0D01		01

11. TITLE (Include Security Classification)
SIMPLE ANALYTICAL METHODS FOR ESTIMATING SHORT-TERM RAINFALL

12. PERSONAL AUTHOR(S)
Wexler, Ruth L.

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Final report	FROM ____ TO ____	November 1986	59

16. SUPPLEMENTARY NOTATION

17. COSATI CODES

FIELD	GROUP	SUB-GROUP
04	02	

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
Climatic index; Daily rainfall; Hourly rainfall; Instantaneous rainfall; Rainfall distributions; Rainfall models; Short-term rainfall

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

Information on short-term rainfall is of interest to agriculturists, hydrologists, geomorphologists, and construction or radar engineers. Short-term rainfall has implication for soil moisture, field operations, electro-optical sensors, and equipment design or malfunction. Military planners are especially concerned with such information because of the impact of rain on mobility and trafficability. Data for rain accumulations over short periods of time are usually not available. Routine climatic precipitation data for much of the world consist of the average monthly and/or annual total amounts of rain and the corresponding number of rain days.

The principal objective of this study is to provide simple analytical methods for recovering the frequency distributions of any short-term rainfall. The required data are the total rainfall for a given period of time and the actual duration of the rain in days, hours, or minutes for estimating daily, hourly, or instantaneous rainfall, respectively. Average

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT: ☐ UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION: Unclassified
22a. NAME OF RESPONSIBLE INDIVIDUAL: Ruth L. Wexler	22b. TELEPHONE (Include Area Code): (202) 355-2846 — 22c. OFFICE SYMBOL: ETL-GS-LB

DD FORM 1473, 84 MAR — 83 APR edition may be used until exhausted. All other editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE
UNCLASSIFIED

19. - Continued

Annual hourly rainfall may be estimated at times as a function of mean annual temperature. Instantaneous rainfall is limited in this study to one-hour storms or rainy periods within storms.

Two rainfall models are provided. The first, the general model, is based mainly on a particular skew distribution that was found previously to represent rainfall under very diverse conditions. This model recovers a considerable range of information for almost any rainfall occurrence. The second, or explicit, model is specific for a given average rain rate. The latter model may be utilized for situations not covered by the general model or as an alternate method. In contrast to certain of the earlier techniques, the above models (a) depend on viable rainfall mass distribution for the situation at hand and (b) determine short-term rainfall, first with respect to the percent frequency of the total duration of the rain and then with respect to real time.

The results yield reasonably accurate short-term rain rates for nearly 98 percent of the rain period. Either model readily determines the percent of time the average rain rate or any selected rain rate is equalled or exceeded. Of significance is the fact that the mean daily, hourly, or instantaneous rain intensity for any duration tends to be greatly exceeded for at least 5 percent of the time. The graphs and computer programs given not only facilitate the rapid estimation of short-term rainfall for almost any situation, but also serve to improve understanding of short-term rainfall spectra.

PREFACE

This report on the determination of short-term rainfall spectra for a broad range of rainfall regimes is part of an Army-wide investigation of Battlefield Obscuration. The results are directed toward the design engineer, who is concerned with the impact of rainfall on materiel, and also toward the field commander, whose ground operations may be hindered or thwarted because of rain. Intense rain causes soil erosion or flooding, hampers mobility, penetrates the protective covering of electrical equipment, reduces visibility, causes microwave attenuation, and contributes to the structural weakening or collapse of roofs. The rainfall models presented, either general or explicit for a given average rain rate, yield quick estimates of daily, hourly, or instantaneous rainfall for much of the respective rainy period. The required parameters are the total rainfall and the duration of rain in the appropriate units of time. Total rain and the number of days of rain per month or year are usually available in most climatic summaries. An hourly rainfall index developed during this study affords a means of approximating the duration of rain in hours per year if not known. The derivation of instantaneous rainfall is limited to single storms. The graphs, equations, and computer programs included in this report facilitate the determination of the frequency of a selected rain rate or, given a selected frequency, the rain rate that would be equalled or exceeded per given interval of time.

The work was accomplished under project QG652CODOI, Work Unit 01, "Frequency and Distribution of Natural Battlefield Obscurants." Appreciation is extended to all personnel in the Battlefield Environmental Effects Group and to Bruce Zimmerman in the Intelligent Systems Group of the Geographic Sciences Laboratory, U.S. Army Engineer Topographic Laboratories, for their helpful suggestions.

The work was performed under the supervision of Dr. Donald W. Dery, Branch Chief, Battlefield Environmental Effects Group; Regis J. Orsinger, Chief, Land Combat Systems Division; and Bruce K. Opitz, Director, Geographic Sciences Laboratory. COL Alan L Laubscher, CE, was Commander and Director, and Walter E. Boge was Technical Director of the U.S. Army Engineer Topographic Laboratories during the report preparation.

CONTENTS

ILLUSTRATIONS

TABLES

SIMPLE ANALYTICAL METHODS FOR ESTIMATING SHORT-TERM RAINFALL

INTRODUCTION

Information on short-term rainfall interests agriculturists, hydrologists, geomorphologists, and construction or radar engineers. Excessive rain can cause flooding, decrease of soil traction, erosion of terrain, structural weakening or collapse of roofs, and malfunction of jet engines because of water ingestion. Intense rain may penetrate the protective covering of electrical equipment, reduce visibility, and cause microwave attenuation. Military planners are concerned with the impact of rain on mobility and trafficability. Data for rain accumulation over short periods of time are generally not available.

Routine precipitation data for much of the world consist of the average monthly and annual total amounts and the corresponding number of days with measurable rain (an amount which varies from one country to another, as greater than or equal to .25 mm or .1 mm for the U.S. or Southeast Asia, respectively). However, a number of weather service bulletins list daily, hourly, or shorter-term precipitation rates, particularly for excessive rain, for various durations, including 5-, 10-, and 15-minute periods (U.S. National Oceanic and Atmospheric Administration 1983; Panama Canal Company 1971).[1 2] Except for instantaneous data, which require more sensitive rain gauges, all hourly rainfall and most daily rainfall utilized refer to rain accumulations equal to or greater than .25 millimeter. For those stations in the tropics for which the 0.1 mm limit applies, the number of days of rain is not very different from that based on the .25 millimeter amount (the difference is of significance in the high latitudes, where the rainfall is much gentler).

From selected weather bulletins or else from specialized experiments at a variety of sites, scientists have developed a number of instantaneous precipitation models (Bussey 1950; Briggs and Harker 1969; Davis and McMorrow1976; Crane 1980; Tattelman and Scharr 1983; Jones and Wedland 1984; Bertheland Plank 1985).[3 4 5 6 7 8] Recently, members of the U.S. Air Force Geophysical Laboratory (AFGL) reviewed in detail and evaluated several models (Tattelman and Grantham 1982).[9] Certain of these models derive short-term rainfall (hourly or instantaneous) directly from total rain and the number of days of rain per year (month). In some instances, additional parameters such as temperature and/or a moisture index are also employed. The AFGL model (Tattelman and Scharr 1983) consists of a set of linear regression equations, each specific for a given percent frequency per year that an estimated instantaneous rainfall is equalled or exceeded.

---

[1] U.S. National Oceanic and Atmospheric Administration (NOAA), *Climatological Data*, annual summary (since 1950).

[2] Panama Canal Company, *Climatological Data*, Canal Zone and Panama, annual reports 1957-1971 (Balboa Heights, Canal Zone).

[3] Howard E. Bussey, "*Microwave Attenuation Statistics Estimated from Rainfall and Water Vapor Statistics*," Proceedings of the Institute of Radio Engineers, vol. 38 (July 1950): 781-785.

[4] Allen R. Davis and Daniel J. McMorrow, *Stochastic Models for Deriving Instantaneous Precipitation Rate Distributions*, Air Weather Service (Scott AFB, Illinois: U.S. Air Force Environmental Technical Applications Center, 1976, AWS-TR-76-263).

[5] R.K. Crane, "*Prediction of Attenuation by Rain*," IEEE Transactions on Communications, COM-28, 9 (1980): 1717-1733.

[6] Douglas M.A. Jones and Wayne M. Wedland, "*Some Statistics of Instantaneous Precipitation*." Journal of Climate and Applied Meteorology (1984): 1273-1285.

[7] J. Briggs and J.A. Harker, "*Estimation of the Duration of Short-Period Rainfall Rates Based on Clock-Hour Values*." The Meteorological Magazine 97 (London, 1969): 246-252.

[8] Robert O. Berthel and Vernon G. Plank, *Time Durations of Rain Rates Exceeding Specified Thresholds* (Hanscom AFB, Massachusetts: U.S. Air Force Geophysics Laboratory, 1985, AFGL-TR-0122).

[9] Paul Tattelman and D.D. Grantham, "*A Survey of Techniques for Determining Short-Duration Precipitation Rate Statistics*." Air Force Surveys in Geophysics, no. 441 (Hanscom AFB, Massachusetts: U.S. Air Force Geophysics Laboratory, 1982, AFGL-TR-82-0357).

Berthel and Plank (1985)[10] showed that percent frequencies of instantaneous rainfall could be estimated by the employment of the coefficient of variation of the rain rate. This coefficient was found to be a function of the ratio of maximum instantaneous rainfall divided by mean instantaneous rainfall. Their technique requires that both parameters for the ratio be obtained or predicted. Davis and McMorrow (1976)[11] and Grantham et al. (1983)[12] provided various stochastic models for deriving instantaneous rainfall from clock-hourly rainfall for selected sites.

From available observations, one may express rainfall accumulation in terms of cumulative percent frequency per rain rate for any unit of time. Hydrologists have long used such rainfall mass distributions for estimating maximum-depth storms or flooding possibilities (World Meteorological Organization 1973).[13]

Olascoago (1950)[14] and Martin (1964)[15] found that when daily rainfall per year is converted to cumulative percent frequency per cumulative percent amount, despite diverse circumstances the results almost invariably tend to approach a particular skew distribution (figure 1). However, Wexler (1967)[16] and Cobb (1968)[17] noted that this average or nearly universal curve does not describe all rainfall, particularly extreme climatic conditions or rainfall singularities. Instead, a family of curves is required to encompass a range of rainfall accumulations, whether daily, hourly, or instantaneous.

The main purpose of this paper is to present two simple models for rapid estimates of short-term rainfall for any unit of time. These are a) the general model (cumulative percent frequency per cumulative percent amount) and b) the explicit model (cumulative percent frequency per rain rate). Each model consists of a number of distributions, which depend on the respective average rain rate per given time.

In addition to a viable rainfall mass distribution for the situation at hand, the essential data consist of the total amount of precipitation (P) and the actual duration of rain in days (D), hours (H), or minutes (M) for estimating daily, hourly, or instantaneous rainfall, respectively. A climatic index simulates the number of hours of rain, if necessary, for limited regions. The only instantaneous rainfalls analyzed are for single storms or for hourly rain. The equations, graphs, and computer programs that are provided facilitate the derivation of short-term rainfall for a wide range of situations.

---

[10] Robert O. Berthel and Vernon G. Plank, *Time Durations of Rain Rates Exceeding Specified Thresholds* (Hanscom AFB, Massachusetts: U.S. Air Force Geophysics Laboratory, 1985, AFGL-TR-0122).

[11] Allen R. Davis and Daniel J. McMorrow, *Stochastic Models for Deriving Instantaneous Precipitation Rate Distributions*. Air Weather Service (Scott AFB, Illinois: U.S. Air Force Environmental Technical Applications Center, 1976, AWS-TR-76-263).

[12] D.D. Grantham et al., "*Water Vapor, Precipitation, Clouds and Fog*: Chapter 16, 1983 Revision," Handbook of Geophysics and Space Environments (Hanscom AFB, Massachusetts: U.S. Air Force Geophysics Laboratory, July 1983, AFGL-TR-83 0181).

[13] World Meteorological Organization, "*Manual for Estimation of Probable Maximum Precipitation*." Operational Hydrology, report no. 1 (Geneva: 1973, WMO no. 332).

[14] M.J. Olascoago, "*Some Aspects of Argentina Rainfall*," Tellus 2 (November 1950): 312.

[15] L.A. Martin, "*An Investigation of the Rainfall Distribution for Stations in North and Central America*," Research on Tropical Rainfall Patterns and Associated Mesoscale Systems, report no. 5 (College Station: Texas A&M University, Dept. of Meteorology, contract DA-IAO-11001-B-021-09, May 1964).

[16] Ruth L. Wexler, "*The Relationship between Daily and Annual Rainfall in Thailand*," Proceedings of the Technical Exchange Conference, Air Weather Service technical report 196 (Washington, D.C.: Air Weather Service, U.S. Air Force, 1967): 226-242.

[17] L.G. Cobb, "*The Annual and Daily Distribution of Rainfall in Southeast Asia*," Research on Tropical Rainfall Patterns and Associated Mesoscale Systems, report no. 4 (College Station: Texas A&M University, Dept. of Meteorology, contract DA-043-AMC-02313(E), December 1968): 53-75.

The data utilized are from a variety of sources, including National Energy Authority, Thailand, 1962-1965; U.S. Army Engineer Division 1968; Sterntein 1962; Environmental Technical Application Center (ETAC) 1962; U.S. Weather Bureau 1960; Winner 1968; and Berthel and Plank 1985 (see references).

THE GENERAL MODEL

The general model is considered first because of its overall applicability. The example of the general model in figure 1, referred to as the "universal" or default rainfall distribution, is used to explain the methodology. This distribution confirms everyday observations that rain tends to fall unevenly, with heavy rain lasting briefly compared to gentler rain. More specifically, this figure indicates that about 10 percent of the rain falls in about 50 percent of the time, whereas nearly 50 percent of the rain falls in just about 10 percent of the time.

By means of a satisfactory equation for the plot in figure 1, one may approximate the original short-term rainfall intensities if the total rainfall and the duration of the rain are known. Unless otherwise stated, the percent frequency refers to the percent of the actual rain days (hours, minutes). One possible equation for the distribution in figure 1 is of the form

$$y = A + B(\ln x) \tag{1}$$

where y = cumulative percent frequency

x = cumulative percent amount of rain

and A and B are constants

A best-fit equation for figure 1 is

$$A = 3.6$$
$$B = 21$$

or

$$y = 3.6 + 21(\ln x) \tag{1a}$$

$$dx/dy \rightarrow = x/B$$

let

$$S = dx/dy \tag{1b}$$

The technique is expounded in terms of daily rainfall, but the method is applicable to any short-term rainfall (hourly or instantaneous) as shown below. Alternate values for the constants A and B are given later for more extreme rainfall, whether very light or very heavy.

At any percent frequency, y, the corresponding rain rate, r, may be found as follows

let	$z = (y-A)/B$	
then	$x = \exp(z)$	
but	$S = x/B$	
therefore	$r = S\ (P/D)$	(1c)
and	$d = (100-y)/100$	(1d)
where	P = total rainfall (mm or inches) D = number of days with measurable rain r = rain rate mm or inches per day, (compatible with P) d = the number of days with rain greater than r	

(For hourly rainfall, substitute H and h for D and d, respectively.)

Figure 2, a graphic aid, i.e., a plot of S versus y, provides a quick way to estimate short-term rainfall with essentially little computation. For instance, for any y, read off S, then multiply by (P/D) to obtain r. As shown later, equation (1a) tends to underestimate r for values of y greater than 95 percent, for which cases extreme-value statistics are indicated (United States Weather Bureau 1955; Hershfield 1972; Fletcher and Sarlos 1951).[18] [19] [20]

Inasmuch as P/D (the ratio employed in most precipitation models) provides a clue to the nature of short-term rainfall, a question raised is, How frequently is this average rain rate (P/D) equalled or exceeded? If $r = P/D$ in equation (1c),

Then	$S = 1$
	$x = B$
and	$y = 67.5\%$
or	$100-y = 32.5\%$

[18] U.S. Weather Bureau, *"Rainfall Intensity-Duration-Frequency Curves for Selected Stations in the United States, Alaska, Hawaiian Islands, and Puerto Rico,"* technical paper no. 25 (1955).
[19] D.M. Hershfield, *"Estimating the Extreme-Value 1-Minute Rainfall,"* Journal of Applied Meteorology 11 (1972): 936-940.
[20] R.D. Fletcher and D. Sarlos, *World Record Rainfall and an Envelope of World Record Values*, Air Weather Service technical report no. 105-81 (Washington, D.C.: Air Weather Service, U.S. Air Force, 1951).

If P/H were substituted for P/D in the above equations, the answer would be the same for hourly rainfall. Bussey (1950)[21] found that for Washington, D.C., the average hourly rain rate, P/H, is equalled or exceeded about 35 percent of the rain hours.

By means of equations (1a) to (1d), short-term rainfall is estimated for various situations (table 1). Tables 1a and 1b compare observed and estimated daily rainfall frequencies per year and month, respectively. Table 1c is similar for hourly frequencies per year. The results appear to be fairly reasonable, considering the fact that all the above estimates are made by means of the distribution in figure 1. Further implications of the results are discussed in more detail later.

Equation (1a) is one of several equations that describe the plot in figure 1. Another is the exponential

$$x = a \exp(by) \tag{2}$$

where a and b are constants

$a = 1.03$

$b = .0455$

x and y are the same as above

then $$x = \exp(.046y) \tag{2a}$$

$$dx/dy = .046\, x$$

and $$S = x/22 \tag{2b}$$

The constant a is rounded off to a value of 1.0 in order to simplify the equation (2a), which, therefore, approximates but does not exactly duplicate equation(1a). Appendix A contains sample problems that are solved by either equation(1a) or (2a).

Despite fairly reasonable estimates of daily or hourly rainfall for the temperate zones and the tropics by means of the universal curve (figure 1), this distribution has its limitations, as mentioned above, particularly with respect to relatively light rain, characteristic of the very high latitudes, or very intense rain, as at certain desert stations, or in very brief storms. Figure 3, therefore, consists of a family of curves (in the format of figure 1) encompassing various rainfall occurrences, as extreme climates or intense storms. These curves represent daily and hourly as well as instantaneous rainfall frequencies based on more than 100 cases. Each curve is a smoothed average of several cases except for the dotted curves, which are only for a single case or two. In a given situation, a particular distribution might approach, but not actually duplicate, any of the above curves. More than half the cases analyzed consist of original observations of daily or hourly rainfall per year or per month.

---

[21] Howard E. Bussey, "*Microwave Attenuation Statistics Estimated from Rainfall and Water Vapor Statistics*," Proceedings of the Institute of Radio Engineers 38 (New York: 1950): 781-785.

The rest are of tabulated class frequencies or previously plotted data of daily or hourly rainfall per year or instantaneous rainfall per single storm. Curve No.1, the leftmost curve in figure 3, represents hourly rainfall for a single year at Pensacola, Florida. The majority of cases fall within the envelope formed by curves No.2 and No.4, with curve No.3 (bold line) being essentially the same as in figure 1. The more extreme the rainfall, the greater the departure from the latter distribution. Table B1 (appendix B) contains constants for equation (1) for the different curves in figure 3. If rainfall accumulations are identified by their respective average rates, as P/D, P/H, or P/M, some tentative distributions based on the numbered curves in figure 3, are as follows:

Curve	Period	Average Rain Rate
2-4	year	P/D: 8.2 to 21.5 mm/day
	year	P/H: 1.2 to 4.0 mm/hour
5	year	P/D > 28.0 mm/day
	year	P/H > 25.0 mm/day
	1 hour	P/M > 50.8 mm/hour (0.9 mm/minute)
6	1 hour	P/M > 127 mm/hour (2.1 mm/minute)

Curves No.5 and No.6 both, then, represent (approximately) the distributions of selected maximum-depth one-hour storms, No.5 for 50 mm (2 inches) and No.6 for 127mm (5 inches). For the first storm, 30 percent of the rain occurs in 10 percent of the time (6 minutes), whereas for the second storm, 22 percent of the rain occurs in 10 percent of the time. If these 6-minute intervals were converted to hourly rates, the results would be 152 mm and 279 mm, respectively. The latter rate is about three-fourths of world-record rainfall for 1 hour (381 mm), as found by Fletcher (1951).[22] For values of y equal to or greater than 70 percent or for distributions with curve numbers greater than 5, an alternate equation is

$$y = a\,x^b \qquad (3)$$

Appendix B contains the respective constants for equation (3) for the above two maximum-depth one-hour storms.

[22] R.D. Fletcher and D. Sarlos, *World Record Rainfall and an Envelop of World Record Values* Air Weather Service technical report no. 105-81 (Washington, D.C., Air Weather Service, U.S. Air Force, 1951).

THE EXPLICIT MODEL

The explicit model consists of a series of rainfall distributions expressed in terms of cumulative percent frequency per rain rate, as in figures 4 and 5. Unless otherwise indicated, each distribution is the average of 3 or more years of annual rainfall data for a given station. In each figure, the selected stations represent a range of daily or hourly rainfall regimes. Although the selection was made at first on the basis of a wide spectrum of total rainfall per year, the resultant plots are not necessarily ordored by rainfall amount.

Figure 4 compares daily (calendar-day) rainfall distributions among stations in Thailand, with total rain from about 1000 mm to over 3000 mm per year. An interesting feature of this figure is the increasing value of P/D from left to right regardless of the individual values of P or D. For P/D of 8 mm/day, less than 10 percent of the rain days are more than 25 mm, whereas for P/D of 31.8 mm/day, nearly 50 percent of the rain days are more than 25 mm. Table 2 lists the original stations and the corresponding annual rainfall represented by these plots.

Figure 5, for hourly (clock-hour) rainfall, shows dramatically the variation of rainfall distributions from the Arctic to the Tropics. As with daily rainfall, the average rain rate in figure 5, i.e. P/H, increases from left to right irrespective of P or H. In the high latitudes (P/H = .6mm/hr), just a small percentage of the rain is more than 2.5 mm/hr (.1 in/hr), whereas in the low latitudes (P/H = 4.0 mm/hr to nearly 6 mm/hr), 40 percent of the rain is more than 2.5 mm/hr. At Roi Et, Thailand, and Veunesai, Cambodia (not shown in figure 5), both with P/H = 5.0 mm/hr, about 50 percent of the rain hours are more than 2.5 mm, and about 10 percent of the hours are more than 12.7 mm. Table 3 lists the stations and corresponding annual hourly rainfall data for the plots in figure 4.

Table 4 lists various percentiles of instantaneous rainfall per hour for essentially continuous rain for average hourly rates of from 0.42 mm/min to 2.12 mm/min (1 inch to 5 inches of rain). These data are from records of excessive rain for periods of 5 minutes to 60 minutes (Panama Canal Company1957-1971).[23]

One equation for the distributions in figures 4 and 5 or table 4 is similar to equation (1) except that R replaces x, that is,

$$y = A + B(\ln R) \tag{4}$$

where R = rain rate

Inasmuch as each of the constants A and B appears to be a function of P/D, P/H, or P/M, intermediary values of either constant may be interpolated accordingly (appendixes B and C). Tables 2 to 4 contain values of the constants, A and B, for equation (4) for the distributions indicated.

[23]Panama Canal Company, *Climatological Data*, Canal Zone and Panama, annual reports 1957-1971 (Balboa Heights, Canal Zone).

As in the case of the general model, the cumulative percent frequency, y, of the average rain rate, P/D (P/H), which identifies the distribution, may be readily computed by means of the explicit model, this time by substituting P/D (P/H) for R in equation (4). For example, for P/D = 21.5 mm/day, A = -27, B = 30.0, and y = 65% (see figure 4).

A single distribution may not be as reliable for the explicit model as a series of distributions for a range of P/D or P/H (or P/M) from which the appropriate constants A and B may be interpolated if necessary. The term "explicit" implies explicit per given P/D (P/H or P/M) in contrast to the general model, where a single distribution may serve a considerable range of daily, hourly, or instantaneous rainfall.

Since the nature of the distribution of short-term rainfall per given situation appears to depend on the respective average rain rate (P/D, P/H, or P/M) for the interval in question, some previous observations are now reexamined (tables 5 to 7). For instance, table 5 (including some of the annual daily rainfall data of table 1) lists 43 Thai stations, with P/D (per year) varying from 8.9 to 24.5 mm/day, respectively, from 10-year-average data. The original observations (from Sternstein 1962)[24] have been converted for this purpose to cumulative percent frequency per rain rate. Table 6 lists daily and hourly frequencies per season and year: 6a is in conventional format; 6b and 6c are in terms of percent frequencies of the actual rain duration, by order of P/D and P/H, respectively. The latter tables show that the cumulative percent frequency per rain rate changes very slowly with increasing P/D(P/H). This fact no doubt accounts for the apparent utility of the universal (default) model. Each of the above tables serves as an explicit model. Table 6c indicates that seasonal rainfall frequencies follow the annual trends, but have greater disparity in their distributions. Moreover, this table shows that two cases of seasonal or annual rainfall with the same P/H do not necessarily have the same P/D (6b), or vice versa. For instance, San Juan-Summer and Hilo-Winter both have a P/H of 2.26 mm/hr, whereas the respective P/D's are 8.31 and 15.42 mm/day. The relationship between H and D(or H and P) apparently has to be established for the situation at hand.

For each unit of time, as a day or an hour, there appears to be a limiting rain rate beyond which the cumulative percent frequencies scarcely vary with increasing P/D or P/H. For example, in table 5, from P/D of 11.4 mm/day to 14.9 mm/day, the frequency for rain of 35 mm a day is about 90 percent. For P/D of 8.9 mm/day to 14.9 mm/day, for a daily rain of 90 mm, the frequencies are all more than 99 percent. In table 7, the frequencies associated with hourly rain greater than 12.7 mm (.50 inch) are similar for values of P/H from 2.8 mm/hr to 5.0 mm/hr. As a consequence, the following formula is utilized for given limits of y or R, namely,

$$y = a\,R^{b} \qquad (5)$$

See appendix B for constants for equation (5).

[24] L. Sternstein, *The Rainfall of Thailand* (Bloomington: Indiana University Foundation Research Division, contract DA-19-129-QM-1582, 1962).

UTILITY OF THE DIFFERENT MODELS

In addition to tables 1a to 1c and appendix A, which give examples of the use of the universal distribution in figure 1, appendix C lists a number of computer programs that show a variety of ways for which both models may be exploited. Unless otherwise stated, only equations (1a) or (2a) are used to demonstrate the general model (the exception being instantaneous rainfall, or the last 2 programs).

The computer programs listed below determine the following, per P and D, H, or M, for the case at hand, namely,

1) DAYRATE: Estimates the number of days per year (month, season) that a given rain rate is equalled or exceeded.

2) HOURRATE: Estimates the number of hours per year (month, season) that selected rain rates are equalled or exceeded.

3) FREQHOUR: Determines the rain rate that is equalled or exceeded 0.1, 0.2, 0.5, 1.0, and 2.0 percent hours per year.

4) TESTDAY: Compares the explicit and the general models for daily rain.

5) TESTHOUR: Compares the explicit and the general models for hourly rain.

6) INSTANT: Determines the deciles of instantaneous rainfall for selected maximum-depth one-hour storms in terms of mm/min.

7) ONE-HOUR: Computes the distributions of instantaneous rainfall for several one-hour storms in terms of mm/hr.

AN HOURLY RAINFALL CLIMATIC INDEX

Inasmuch as the number of hours of rain (H) is not usually available, it must often be obtained by indirect means. Table 8 lists P, D, and H for selected stations. On a worldwide basis, H/D = 4.0, approximately. However,this ratio, somewhat erratic, tends to be higher in the colder regions than in the warmer. From the high to the low latitudes, P/H varies from 0.6 mm/hr(.02 inches/hr) to about 10 times that rate, respectively. Let J = H/P: then for any annual rainfall, J may be roughly estimated (r^2=.76) from mean annual temperature (°C) by

$$J = .0447(C) + 1.43 \tag{6}$$

where J is in hours/mm

Equation (6) does not apply to stations with P/H greater than 4.0 mm/hr. Once J is established for a particular climatic zone, then for any station in the respective area, H = P(J).

In any given region, the value of J may be locally influenced by exposure to the moist air flow or by terrain. For rainfall in Indonesia (Mohr and VanBaren 1954)[25], for instance, J tends to increase somewhat with elevation.

DISCUSSION

The greatest advantage of the general model is its wide applicability, that is, the use of essentially a single distribution for a considerable variety of circumstances. Moreover, for a given situation, the constants for the general model remain the same no matter what the data units (inches/day or mm/day). For the explicit model, the constant A has to be converted with change of unit, whereas B remains the same. For instance, A(inches)=A(mm) +B(1n 25.4). For either model, the relative stability of rainfall distributions in terms of percentiles provides a means of checking data errors. The main disadvantage of the general model is that unless the data represent a long-term average, a single extreme rain rate on occasion may considerably bias the resultant distribution.

The advantage of the explicit model is that one may sometimes estimate rain rate frequencies merely by inspection (or interpolation) of the appropriate graph or table. This model provides a guide to the limiting values of the short-term rainfall intensities (per rainy period) in the natural environment (figures 4 and 5). The drier the climate (or season), the greater the dearth of low intensity daily (or hourly) rainfall. For instance, for 3 years, 1962-1964, of rainfall at Sisaket, Thailand, with P/D values of 38.4, 27.5, and 28.2 mm/day and D of 50, 54, and 30, respectively, there was not a single rain day with less than 4 millimeters of rain. The colder the climate (or season), the greater the percentage of very light rainfall per day or hour. For annual daily rainfall, a limiting distribution (see figure 4) is reached at about 30 mm/day (calendar-day). Any higher average daily rain rate often (not always) results from a single day of highly unusual rainfall. For annual clock-hourly rainfall, the limit is about 5 mm per hour (see table 7). For continuous (instantaneous) rainfall, some measure of the total range of the instantaneous intensities seems to be required (Berthel and Plank1985)[26], a factor which might also improve extreme daily or hourly rainfall. For one-hour storms of 50.8 mm and 127 mm, the range of instantaneous rates appears to be greater in the U.S. Weather Bureau examples than at the Canal Zone and Panama (compare the results of the programs, INSTANT and ONE-HOUR, appendix C).

---

[25] E.C.J. Mohr and F.A. Van Baren, *Tropical Soils* (London: Interscience Publishers, Ltd., 1954).

[26] Robert O. Berthel and Vernon G. Plank, *Time Durations of Rain Rates Exceeding Sepcified Thresholds* (Hanscom AFB, Massachusetts: U.S. Air Force Geophysics Laboratory, 1985, AFGL-TR-0122).

SUMMARY AND CONCLUSIONS

1. Despite the vagaries of rainfall and the diversity of circumstances, for any one year or for a single storm the rainfall distributions determined so far are surprisingly reproducible in terms of cumulative percent frequency per cumulative percent amount or else cumulative percent frequency per rain rate, for a given P/D (P/H or P/M), regardless of the individual values of P and D (H or M).

2. As a consequence of the above observations, equations, graphs, and computer programs are presented to facilitate the recovery of a variety of information concerning short-term rainfall, particularly its frequency.

3. Although the ratio P/D (P/H or P/M) is the most significant factor in the determination of short-term rainfall frequencies, the actual duration of rain, that is D (H or M), is essential for converting the percent frequencies to durations in real time.

4. The hourly rainfall climatic index, H/P or J, seems to be a useful tool for deriving H when only P is known.

5. For annual rainfall, the average rain rate, P/D (or P/H), is exceeded about 32 percent to 35 percent of the rain period.

6. Short-term rainfall distributions tend to become less skewed as the average rain rate per given interval of time approaches extreme values.

7. In general, hourly rainfall intensities increase with temperature and decrease with elevation.

8. Since short-term rainfall has implication for soil moisture, field operations, electro-optical sensors, and equipment design or malfunction, the above results should provide invaluable engineering guidance. Military planners should benefit by improved understanding of the likely impact of rainfall over short periods of time with respect to mobility or trafficability.

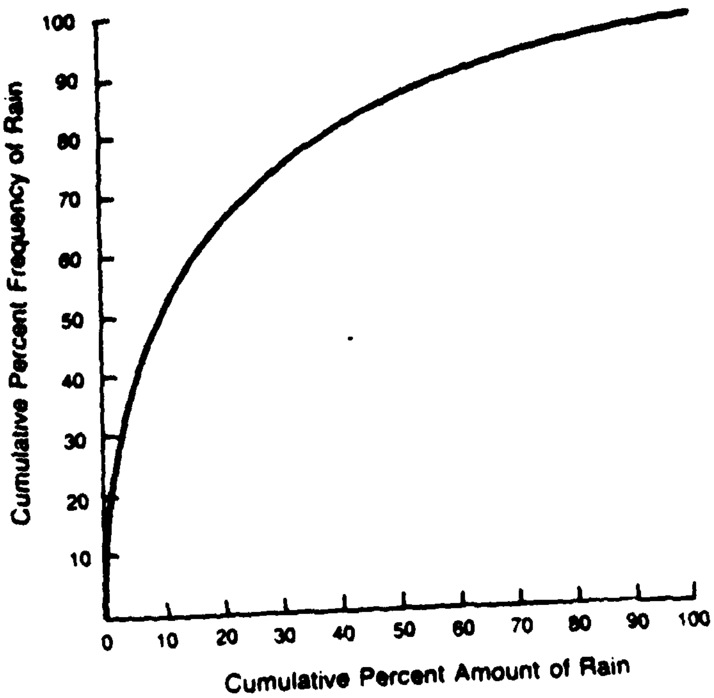


Figure 1. Average rainfall mass distribution.

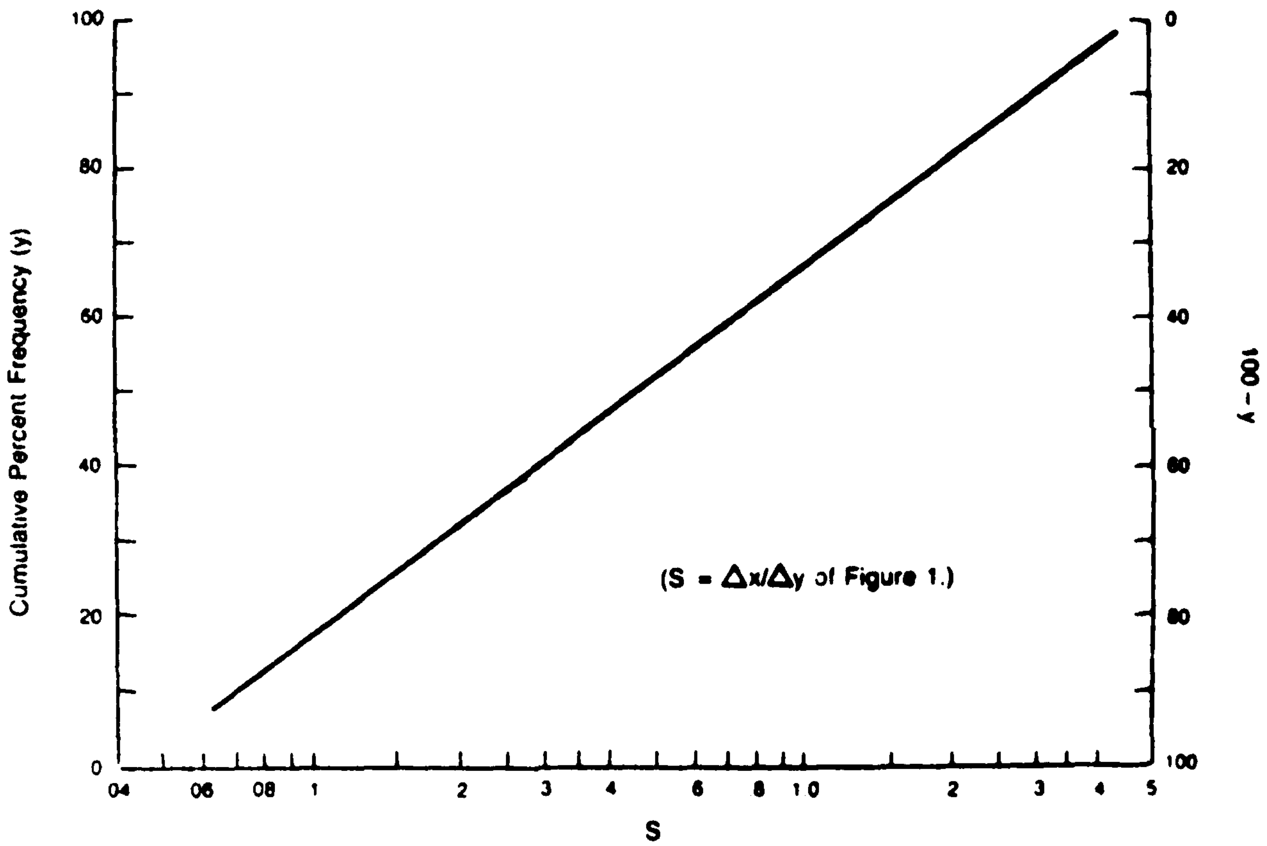


Figure 2. Graphic aid: S versus y.

Note: For the percentile of any daily rain, read off S at selected y, then multiply S by P/D to obtain the required rate, r. Similarly, for hourly rain, multiply S by P/H.

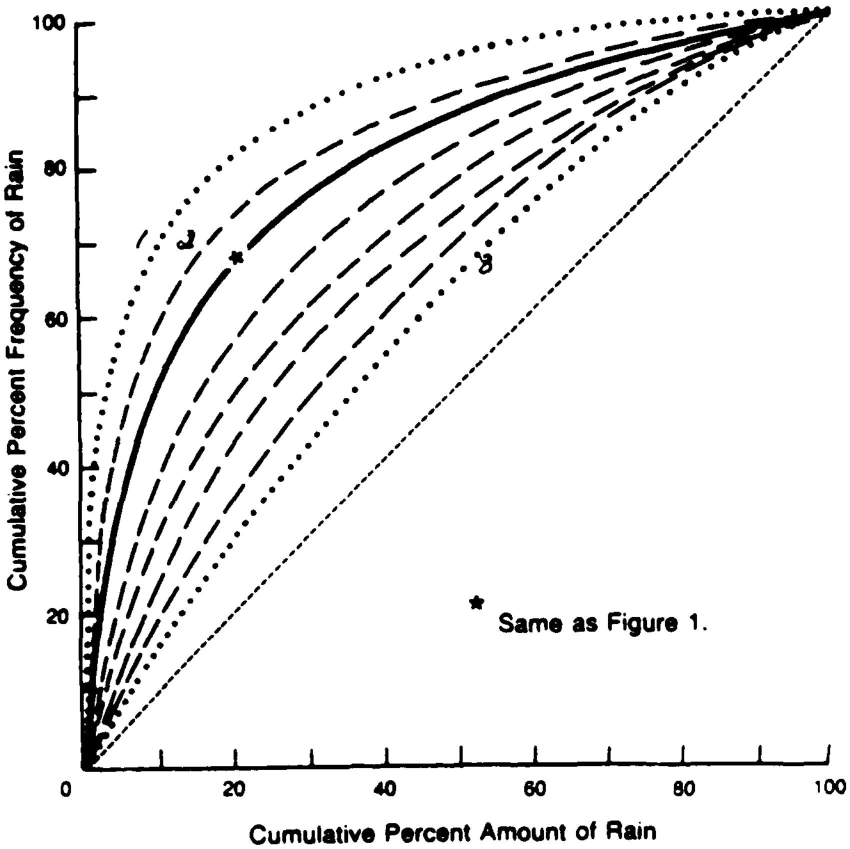


Figure 3. Set of rainfall distributions.

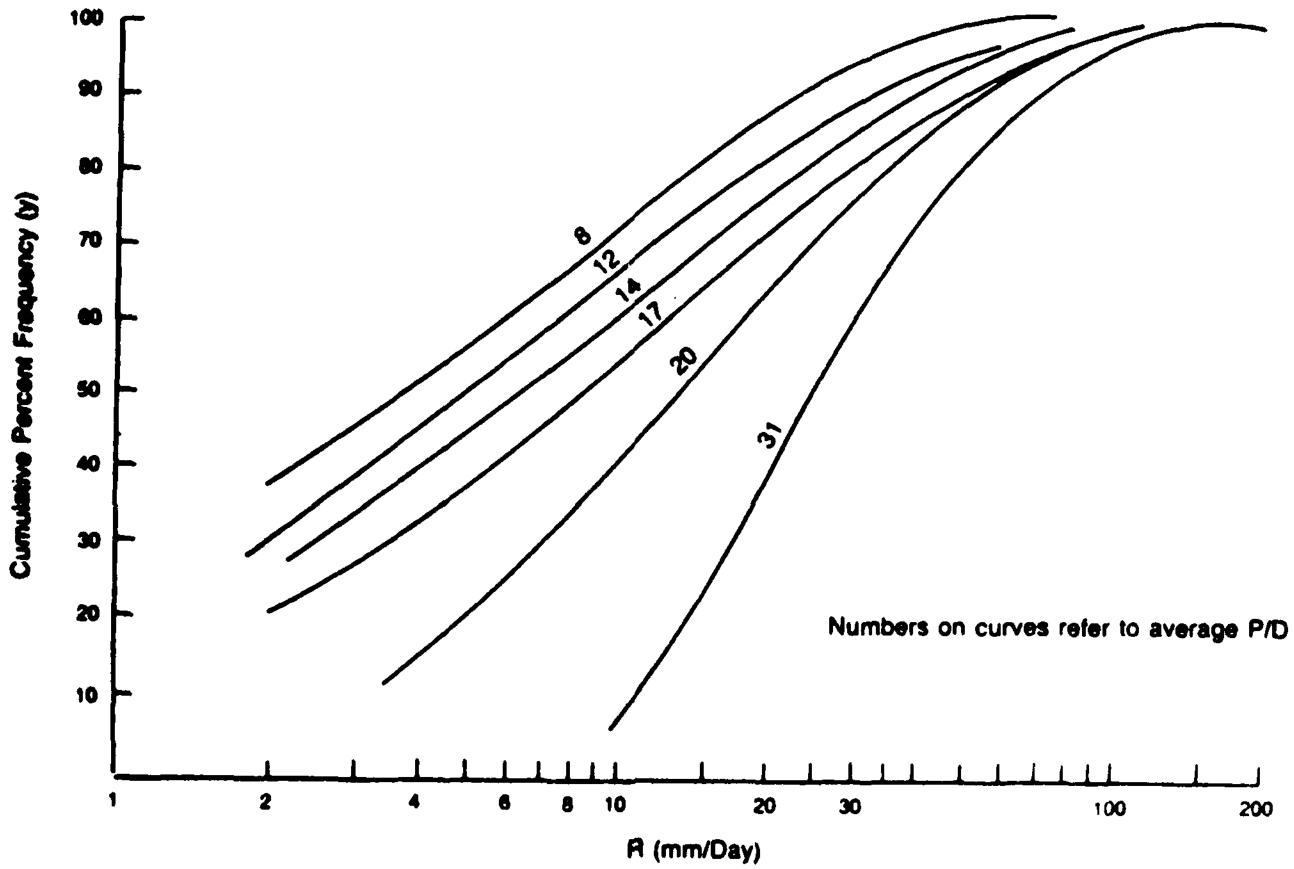


Figure 4. Cumulative percent frequency of daily rain.

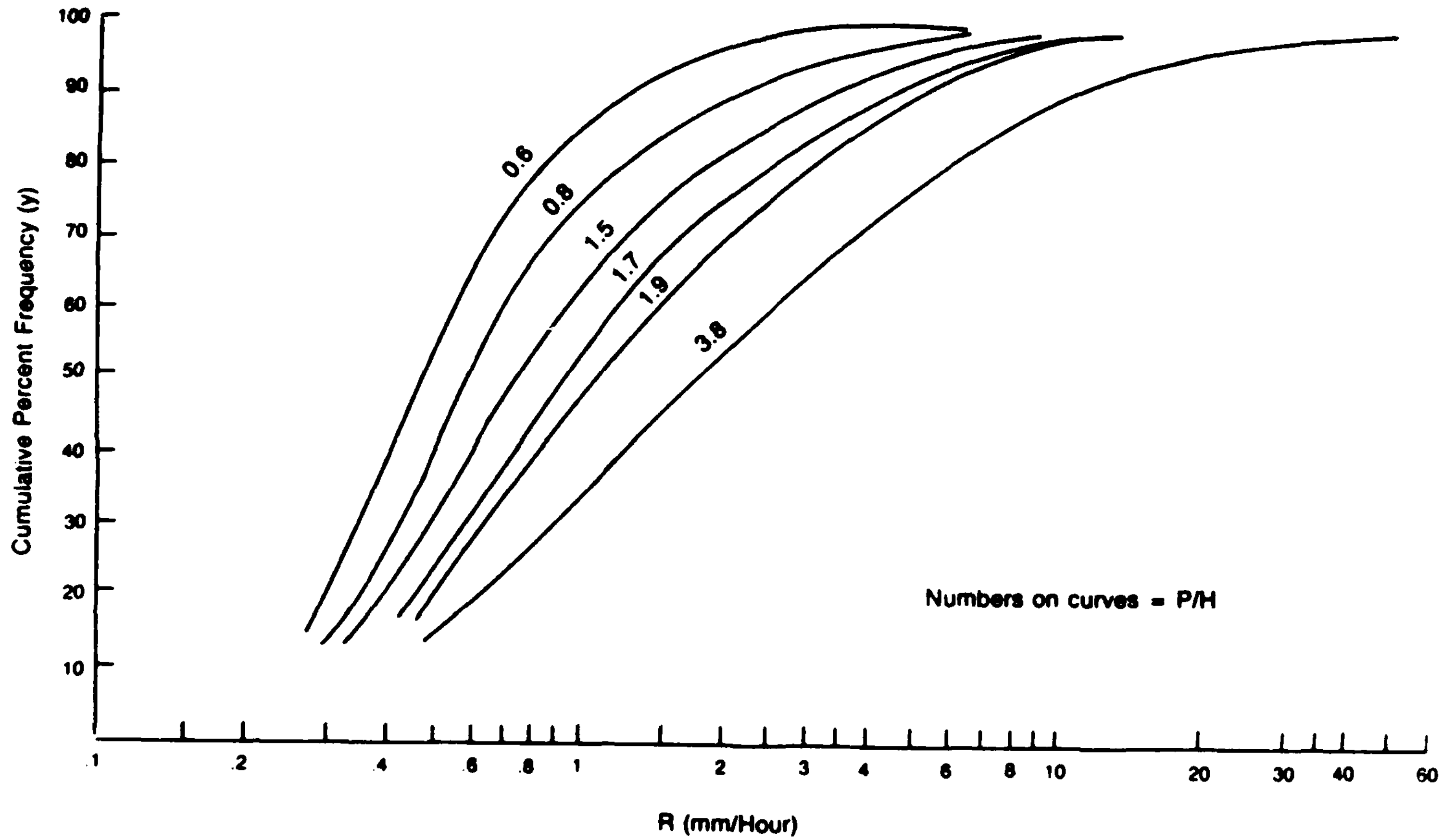


Figure 5. Cumulative percent frequency of hourly rain.

DAILY RAIN FREQUENCIES PER YEAR: THAILAND

				NO. DAYS WITH RAIN >= AMOUNT GIVEN			
				10 MM		35 MM	
STA#	STATION	P (MM)	D	OBS	EST	OBS	EST
500	P. KHIRIKHAN	1019	124	28.0	35.1	8.0	2.5
330	PHRAE	1022	90	31.0	31.6	6.0	7.9
325	MAE SARIANG	1149	125	37.0	38.4	2.0	5.5
300	MAE HONGSON	1255	112	38.0	39.0	7.0	9.6
351	UTTARADIT	1403	117	41.0	42.4	9.0	11.7
456	DON MUANG	1604	134	47.0	48.6	10.0	13.3
462	ARANYAPRATHET	1690	132	48.0	49.7	11.0	15.0
517	CHUMPON	1991	175	57.0	61.6	11.0	15.5
568	SONGKHLA	2184	174	49.0	64.8	12.0	19.0
552	N. S. THAMMARAT	2378	189	64.0	70.5	23.0	20.8
567	TRANG	2564	159	68.0	67.6	16.0	25.7
583	NARATHIWAT	2600	159	62.0	68.0	20.0	26.2
480	CHANTHABURI	3305	171	78.0	79.2	29.0	34.2
532	RAMONG	4347	207	105.0	99.5	39.0	45.0
501	KHLONG YAI	4922	192	104.0	100.3	45.0	49.8

Table 1. Observed and estimated short-term rainfall.

b DAILY RAINFALL FREQUENCIES PER MONTH

BROCKEN, GERMANY

	P (MM)	D	NO. DAYS WITH RAIN >= 1.0 MM OBS	1.0 MM EST	10 MM OBS	10 MM EST
J	149.9	20	18.0	14.9	6.0	5.2
F	175.3	17	14.0	13.8	4.0	5.6
M	144.8	19	15.0	14.2	4.0	5.0
A	109.2	18	15.0	12.6	3.0	3.9
M	99.1	17	13.0	11.8	3.0	3.5
J	142.2	18	14.0	13.6	4.0	4.9
J	160.0	20	15.0	15.2	5.0	5.5
A	149.9	20	15.0	14.9	5.0	5.2
S	116.8	19	14.0	13.4	4.0	4.2
O	114.3	20	15.0	13.7	4.0	4.1
N	129.5	20	16.0	14.3	4.0	4.6
D	162.6	21	18.0	15.8	5.0	5.6
A	1653.5	230	182.0	169.2	49.0	58.0

Table 1. Observed and estimated short-term rainfall. (cont)

c HOURLY RAIN FREQUENCIES PER YEAR

			NO. HOURS WITH RAIN > MM/HR INDICATED					
			1.27		2.54		6.35	
STATION	P(MM)	H	OBS	EST	OBS	EST	OBS	EST
WASHINGTON	1064.3	635.0	240.0	243.1	112.0	150.7	30.0	28.5
PESHAWAR	373.4	109.0	59.5	58.1	39.3	42.2	19.4	21.3
TOWNSVILLE	1160.8	364.0	189.0	188.5	116.0	135.6	51.0	65.5
CLARK	1762.8	551.0	286.0	285.8	175.0	205.6	77.0	99.6
CEYLON	2286.0	607.0	360.0	335.6	237.0	247.3	106.0	130.5
HONOLULU	533.4	265.0	92.0	111.7	52.0	73.1	20.0	22.1
CUAM	2260.6	1177.0	515.0	484.4	265.0	313.0	77.0	86.5
LOEI	1026.2	367.0	159.0	180.0	97.0	126.5	40.0	55.9
KRAKOR	1292.9	388.0	178.0	204.6	123.0	148.1	57.0	73.4

Table 1. Observed and estimated short-term rainfall. (con)

NUMBER DAYS PER YEAR WITH RAIN >=R

P/D	8.2	11.7	14.3	16.9	21.8	31.6
R(MM/DAY)						
1	100.1	86.4	93.3	155.0	55.0	44.7
2	86.7	75.7	81.1	143.1	53.4	44.7
4	65.7	58.4	65.0	123.0	48.3	44.7
8	45.4	40.4	47.7	92.0	37.3	42.4
12	32.3	32.7	37.7	70.3	30.7	37.1
16	21.0	26.9	29.0	60.0	25.0	30.4
20	16.4	22.3	22.6	51.2	20.8	27.0
24	10.4	17.9	19.0	44.8	18.4	20.7
32	7.0	9.7	15.3	30.2	12.0	14.3
40	4.4	7.3	10.2	25.3	9.0	10.7
48	1.4	5.0	8.1	17.0	6.7	8.0
56	1.4	2.7	3.8	13.0	4.3	6.7
64	0.7	2.5	3.1	10.1	2.7	5.0
72	0.7	1.8	3.1	7.0	2.1	4.0
80	0.7	1.1	2.4	5.1	1.0	2.4
96	0.4	0.3	1.0	0.9	1.0	1.7
120	0.1	0.0	1.0	0.9	0.7	0.7
STATION	LOEI	KHON KAEN	ROI ET	B.N.PRUE	PHOL	SRISAKET
P(MM)	1131.6	1264.4	1564.3	3085.0	1242.5	1413.9
D	138.0	107.7	109.3	183.0	57.0	44.7
A *	25.0	17.7	12.8	9.4	-27.0	-80.9
B	21.0	20.5	21.0	20.7	30.0	41.0

Table 2. Daily rainfall frequency observations.

*Constants for equation (4)

NUMBER HOURS PER YEAR WITH RAIN >=R

P/H	0.7	0.8	1.5	1.7	1.9	3.8
R(MM/HR)						
0.51	84.4	392.2	236.6	469.9	894.5	503.8
1.27	17.8	134.0	101.9	240.0	515.5	360.0
2.54	3.8	47.1	49.1	111.8	264.8	236.7
5.08	0.2	21.4	21.8	38.1	117.7	133.5
6.35	0.2	7.8	13.5	29.8	76.5	106.2
12.70	0.1	2.1	2.9	7.6	22.4	40.7
19.05	0.0	1.4	1.5	4.4	14.1	18.2
25.40	0.0	0.4	0.6	1.3	3.3	12.1
38.10	0.0	0.4	0.1	0.3	0.8	1.6
STATION	THULE	PARIS	N.PLATTE	WASH.D.C.	GUAM	CEYLON
P(MM)	139.7	569.0	541.0	1064.3	2260.6	2286.0
H	211.0	713.0	364.0	635.0	1177.0	607.0
A *	81.1	67.6	58.2	50.3	46.5	35.3
B	28.8	26.6	24.6	28.7	28.3	23.4

Table 3. Hourly rainfall frequency observations.

*Constants for equation (4)

PERCENTILES OF ONE-HOUR EXCESSIVE RAIN, CANAL ZONE: MM/MIN

CUM % FREQ	0.42	0.85	1.27	1.69	2.12
25.0	0.11	0.29	0.52	0.79	1.07
33.3	0.14	0.37	0.64	0.93	1.24
41.7	0.19	0.46	0.77	1.11	1.44
50.0	0.25	0.57	0.94	1.31	1.68
58.3	0.32	0.72	1.14	1.55	1.95
66.7	0.42	0.90	1.38	1.84	2.27
75.0	0.55	1.12	1.67	2.18	2.65
83.3	0.72	1.41	2.03	2.59	3.08
91.7	0.94	1.76	2.46	3.07	3.58
100.0	1.23	2.20	2.99	3.64	4.17
A *	93.5	70.8	52.9	36.7	21.4
B	31.2	37.2	43.1	49.0	54.9

Table 4. Instantaneous rainfall frequency observations.

*Constants for equation (4)

				NO. DAYS > R			CUMULATIVE PERCENT FREQUENCY		
STA#	P/D	P	D	10 MM	35 MM	90 MM	10 MM	35 MM	90 MM
353	8.90	1182.9	132.9	34.3	6.0	0.5	74.2	95.5	99.6
475	8.92	1045.5	117.2	29.5	6.0	0.8	74.8	94.9	99.3
325	9.18	1175.0	128.0	38.6	6.1	0.3	69.8	95.2	99.8
376	9.92	1032.9	104.1	29.6	6.1	0.8	71.6	94.1	99.2
379	9.59	1192.0	124.3	38.0	7.8	0.5	69.4	93.7	99.6
450	9.83	1181.1	120.1	32.8	8.1	0.3	72.7	93.3	99.8
500	9.99	1216.2	121.8	27.7	6.1	0.3	77.3	95.0	99.8
431	10.21	1178.7	115.5	36.4	7.2	0.6	68.5	93.8	99.5
477	10.45	1264.9	121.0	36.5	7.8	0.9	69.8	93.6	99.3
327	10.79	1328.9	123.2	40.6	9.6	0.5	67.0	92.2	99.6
459	10.88	1423.6	130.8	40.4	7.8	0.9	69.1	94.0	99.3
328	10.87	1164.2	107.1	31.7	5.7	0.2	70.4	94.7	99.8
331	10.92	1247.3	114.2	39.2	7.2	0.8	65.7	93.7	99.3
300	10.98	1313.5	119.6	38.6	6.4	0.5	67.7	94.6	99.6

Table 5. Annual daily rainfall per P/D: Thai stations.

				NO. DAYS > R			CUMULATIVE PERCENT FREQUENCY		
STA#	P/D	P	D	10 MM	35 MM	90 MM	10 MM	35 MM	90 MM
381	11.05	1251.1	113.2	34.2	8.5	0.8	69.8	92.5	99.3
432	11.02	1339.5	121.5	36.6	8.7	0.6	69.9	92.8	99.5
356	11.14	1394.5	125.2	39.7	9.8	1.1	68.3	92.2	99.1
375	11.14	1513.4	135.8	33.6	8.0	0.9	75.3	94.1	99.3
551	11.29	1877.1	166.2	47.9	10.3	1.7	71.2	93.8	99.0
517	11.34	2025.5	178.6	57.7	12.2	1.2	67.7	93.2	99.3
330	11.37	1022.5	89.9	30.9	6.1	0.3	65.6	93.2	99.7
462	11.37	1594.1	140.2	47.9	12.8	0.9	65.8	90.9	99.4
456	11.49	1546.7	134.6	44.8	12.2	1.1	66.7	90.9	99.2
400	11.50	1190.9	103.6	36.1	7.9	0.3	65.2	92.4	99.7
455	11.46	1490.6	130.1	45.2	10.4	0.6	65.3	92.0	99.5
354	11.52	1475.1	128.0	41.5	11.8	0.9	67.6	90.8	99.3
378	11.68	1392.8	119.2	34.5	8.4	0.6	71.1	93.0	99.5
407	12.26	1572.8	128.3	43.7	10.4	0.9	65.9	91.9	99.3

Table 5. Annual daily rainfall per P/D: Thai stations. (cont)

				NO. DAYS > R			CUMULATIVE PERCENT FREQUENCY		
STA#	P/D	P	D	10 MM	35 MM	90 MM	10 MM	35 MM	90 MM
407	12.26	1572.8	128.3	43.7	10.4	0.9	65.9	91.9	99.3
383	12.43	1408.5	113.3	40.0	11.5	0.8	64.7	89.8	99.3
351	12.44	1488.3	119.6	37.0	12.2	1.1	69.1	89.8	99.1
568	12.57	2183.9	173.7	52.0	14.7	2.5	70.1	91.5	98.6
426	12.67	1375.9	108.6	38.1	9.9	1.1	64.9	90.9	99.0
425	13.07	1353.2	103.5	38.5	11.0	1.2	62.8	89.4	98.8
405	13.48	1442.7	107.0	38.0	10.5	0.6	64.5	90.2	99.4
303	14.27	1813.1	127.1	55.1	13.6	0.9	56.6	89.3	99.3
430	14.57	1988.0	136.4	58.2	14.2	1.2	57.3	89.6	99.1
564	14.68	2414.2	164.5	70.6	16.5	1.5	57.1	90.0	99.1
552	14.90	2559.7	171.8	59.6	18.7	4.0	65.3	89.1	97.7
357	15.82	2119.8	134.0	55.5	17.6	2.0	58.6	86.9	98.5
583	16.61	2709.8	163.1	61.6	19.4	3.5	62.2	88.1	97.9
480	18.66	3214.9	172.3	77.5	28.4	5.7	55.0	83.5	96.7
532	22.00	4390.7	199.6	105.9	39.9	7.0	46.9	80.0	96.5
501	24.48	4824.4	197.1	103.5	44.3	10.7	47.5	77.5	94.6

Table 5. Annual daily rainfall per P/D: Thai stations.(cont)

a. OBSERVATIONS IN ORIGINAL FORMAT

	P	D	NO. DAYS > MM GIVEN			H	NO. HOURS > MM GIVEN		
			6.35	12.7	25.4		6.35	12.7	25.4
WASH.D.C.									
WI	237.0	29.4	12.6	2.6	2.2	191.6	3.4	0.2	0.0
SP	246.6	30.8	13.2	6.8	1.8	163.0	2.6	1.2	0.2
SU	316.7	29.2	12.8	8.6	3.6	99.6	13.8	5.4	1.2
AU	202.2	24.0	10.2	5.0	1.6	121.8	6.4	0.8	0.0
YR	1002.8	113.4	48.8	23.0	9.2	576.0	26.2	7.6	1.4
TUCSON									
WI	58.9	11.2	3.4	1.2	0.2	47.8	0.4	0.0	0.0
SP	22.9	6.6	1.2	0.2	0.0	24.8	0.2	0.0	0.0
SU	142.7	25.8	5.2	2.6	0.8	64.0	6.6	2.2	0.4
AU	47.2	8.4	2.8	1.2	0.0	32.8	0.6	0.0	0.0
YR	271.5	52.0	12.6	5.2	1.0	169.4	7.6	2.2	0.4
PENSACOLA									
WI	297.9	30.2	12.8	8.0	3.0	140.6	10.4	3.0	0.2
SP	427.0	27.8	16.0	11.8	6.4	132.6	19.4	6.8	1.4
SU	464.6	35.6	17.4	13.0	5.2	126.0	21.1	8.8	2.2
AU	572.5	28.6	15.5	12.2	8.4	151.8	26.4	10.2	3.0
YR	1762.0	122.2	61.7	45.0	23.0	551.0	77.4	28.8	6.8
HILO									
WI	830.1	53.8	29.8	20.4	9.8	368.2	26.8	6.4	1.2
SP	617.0	70.8	30.8	14.2	4.0	414.0	13.2	2.4	0.2
SU	745.7	81.8	35.0	17.0	3.8	443.4	18.6	4.6	0.8
AU	970.5	75.8	34.6	18.2	7.2	439.2	33.2	12.8	2.0
YR	3163.3	282.8	130.2	69.8	24.8	1664.8	91.8	26.2	4.2
SAN JUAN									
WI	278.1	46.8	12.2	5.4	1.8	156.0	7.2	2.6	1.0
SP	320.8	42.8	11.8	7.2	3.4	139.6	11.6	4.4	1.4
SU	479.6	57.8	21.6	12.6	5.4	212.6	20.6	5.0	0.2
AU	421.1	51.8	19.2	8.8	4.4	173.4	15.4	4.6	2.0
YR	1499.9	199.2	64.8	34.0	15.0	681.6	54.8	16.6	4.6

Table 6. Seasonal daily and hourly rainfall: 5 stations.

b. CUMULATIVE PERCENT FREQUENCY PER DAILY RAIN PER P/D
(SEASON/YEAR): REORDERED OBSERVATIONS

STA-SEAS/YR	P/D(MM/DAY)	6.35 MM	12.7 MM	25.4 MM
TU-SP	3.45	81.8	97.0	100.0
TU-YR*	5.23	75.8	90.0	98.1
TU-WI	5.26	69.6	89.3	98.2
TU-SU	5.54	79.8	89.9	96.9
TU-AU	5.61	66.7	85.7	100.0
SJ-WI	5.94	73.9	88.5	96.2
SJ-SP	7.49	72.4	83.2	92.1
SJ-YR*	7.52	67.5	82.9	92.5
DC-SP	8.00	57.1	77.9	94.2
DC-WI	8.05	57.1	91.2	92.5
SJ-AU	8.13	62.9	83.0	91.5
SJ-SU	8.31	62.6	78.2	90.7
DC-AU	8.43	57.5	79.2	93.3
HI-SP	8.71	56.5	79.9	94.4
DC-YR*	8.84	57.0	79.7	91.9
HI-SU	9.12	57.2	79.2	95.4
PE-WI	9.86	57.6	73.5	90.1
DC-SU	10.85	56.2	70.5	87.7
HI-YR*	11.18	54.0	75.3	91.2
HI-AU	12.80	54.4	76.0	90.5
PE-SU	13.06	51.1	63.5	85.4
PE-YR*	14.43	49.5	63.2	81.2
PE-SP	15.37	42.4	57.6	77.0
HI-WI	15.42	44.6	62.1	81.8
PE-AU	20.02	45.8	57.3	70.6

* ANNUAL DATA

Table 6. Seasonal daily and hourly rainfall: 5 stations. (cont)

c CUMULATIVE PERCENT FREQUENCY PER HOURLY RAIN PER P/H
(SEASON/YEAR): REORDERED OBSERVATIONS

STA-SEAS/YR	P/H(MM/HR)	6.35 MM	12.7 MM	25.4 MM
TU-SP	0.91	99.2	100.0	100.0
TU-WI	1.24	99.2	100.0	100.0
DC-WI	1.24	98.2	99.9	100.0
TU-AU	1.45	98.2	100.0	100.0
HI-SP	1.50	96.8	99.4	100.0
DC-SP	1.52	98.4	99.3	99.9
TU-YR*	1.60	95.5	98.7	99.8
DC-AU	1.65	94.7	99.3	100.0
HI-SU	1.68	95.8	99.0	99.8
DC-YR*	1.75	95.5	98.7	99.8
SJ-WI	1.78	95.4	98.9	99.4
HI-YR*	1.90	94.5	98.4	99.8
PE-WI	2.11	92.6	97.9	99.9
SJ-YR*	2.21	92.0	97.6	99.3
HI-AU	2.21	92.4	97.1	99.5
TU-SU	2.24	89.7	96.6	99.4
SJ-SU	2.26	90.3	97.6	99.9
HI-WI	2.26	92.7	98.3	99.7
SJ-SP	2.29	91.7	96.8	99.0
SJ-AU	2.44	91.1	97.3	98.8
DC-SU	3.18	86.1	94.6	98.8
PE-YR*	3.20	86.0	94.8	98.8
PE-SP	3.23	85.4	94.9	98.9
PE-SU	3.68	83.3	93.0	98.3
PE-AU	3.76	82.6	93.3	98.0

* ANNUAL DATA

Table 6. Seasonal daily and hourly rainfall: 5 stations. (cont)

OBSERVATIONS OF TROPICAL RAINFALL: THAILAND AND CAMBODIA

STATION	P(MM)	H	P/H	# NUMBER OF HOURS PER YEAR WITH RAIN >= MM/HR INDICATED 0.51	1.27	2.54	5.08	6.35	12.70	19.05	25.40	38.10	50.80
LOEI	1026.2	367.0	2.80	289.0	159.0	97.0	52.0	40.0	14.0	6.0	3.0	0.1	0.0
KRAKOR	1292.9	388.0	3.33	318.0	178.0	123.0	67.0	57.0	25.0	11.0	7.0	2.0	0.5
SURIN	1391.9	385.0	3.62	312.0	171.0	111.0	64.0	54.0	28.0	13.0	8.0	4.0	1.0
BATTAMBANG	1409.7	386.0	3.65	312.0	204.0	142.0	78.0	62.0	30.0	14.5	6.0	3.0	1.0
STUNG TRENG	1564.6	427.0	3.66	366.0	228.0	145.0	72.0	60.0	30.0	15.0	11.0	3.0	0.0
KORAT	1135.4	303.0	3.75	260.0	162.0	109.0	61.0	47.0	22.0	9.0	6.0	1.0	0.5
KRATIE	1145.5	288.0	3.98	253.0	156.0	110.0	58.0	47.0	24.0	8.5	5.5	0.5	0.0
DAP BAT	1153.2	281.0	4.10	248.0	146.0	99.0	62.0	53.0	24.0	10.0	5.5	1.5	0.0
O RAING	2415.5	568.0	4.25	555.0	340.0	252.0	137.0	109.0	44.0	19.5	9.5	3.5	1.0
LOMPHAT	1564.6	360.0	4.35	358.0	210.0	158.0	72.0	63.0	21.0	8.5	4.0	1.0	1.0
SVAY RIENG	1643.4	362.0	4.54	314.0	199.0	139.0	85.0	74.0	38.0	19.5	10.0	2.0	0.0
ROI ET	1176.0	240.0	4.90	233.0	171.0	118.0	61.0	52.0	23.0	11.5	7.5	1.0	1.0
VEUNESAI	2100.6	414.0	5.07	405.0	317.0	222.0	126.0	100.0	39.0	19.0	11.0	4.0	2.0

Table 7. Hourly rainfall per P/H: Tropical stations.

b. CUMULATIVE PERCENT FREQUENCY OF RAIN HOURS PER YEAR

STATION	P(MM)	H	P/H	0.51	1.27	2.54	5.08	6.35	12.70	19.05	25.40	38.10	50.80
LOEI	1026.2	367.0	2.80	21.3	56.7	73.6	85.8	89.1	96.2	98.4	99.2	100.0	100.0
KRAKOR	1292.9	388.0	3.33	18.0	54.1	68.3	82.7	85.3	93.6	97.2	98.2	99.5	99.9
SURIN	1391.9	385.0	3.62	19.0	55.6	71.2	83.4	86.0	92.7	96.6	97.9	99.0	99.7
BATTAMBANG	1409.7	386.0	3.65	19.2	47.2	63.2	79.8	83.9	92.2	96.2	98.4	99.2	99.7
STUNG TRENG	1564.6	427.0	3.66	14.3	46.6	66.0	83.1	85.9	93.0	96.5	97.4	99.3	100.0
KORAT	1135.4	303.0	3.75	14.2	46.5	64.0	79.9	84.5	92.7	97.0	98.0	99.7	99.8
KRATIE	1145.5	288.0	3.98	12.2	45.8	61.8	79.9	83.7	91.7	97.0	98.1	99.8	100.0
DAP BAT	1153.2	281.0	4.10	11.7	48.0	64.8	77.9	81.1	91.5	96.4	98.0	99.5	100.0
O RAING	2415.5	568.0	4.25	2.3	40.1	55.6	75.9	80.8	92.3	96.6	98.3	99.4	99.8
LOMPHAT	1564.6	360.0	4.35	0.6	41.7	56.1	80.0	82.5	94.2	97.6	98.9	99.7	99.7
SVAY RIENG	1643.4	362.0	4.54	13.3	45.0	61.6	76.5	79.6	89.5	94.6	97.2	99.4	100.0
ROI ET	1176.0	240.0	4.90	2.9	28.8	50.8	74.6	78.3	90.4	95.2	96.9	99.6	99.6
VEUNESAI	2100.6	414.0	5.07	2.2	23.4	46.4	69.6	75.8	90.6	95.4	97.3	99.0	99.5

Table 7. Hourly rainfall per P/H: Tropical stations. (cont)

STATION	P	D	H	H/D	P/D	P/H
HIGH-LAT	(MM)					

THULE AB	139.7	65.0	211.0	3.2	2.1	0.66
BARROW	127.0	100.0	291.0	2.9	1.3	0.44
FAIRBANKS	228.6	94.0	370.0	3.9	2.4	0.62
CLEAR	292.1	100.0	507.0	5.1	2.9	0.58
ST. PAUL IS.	584.2	199.0	1014.0	5.1	2.9	0.58
MID-LAT						

PARIS	569.0	148.0	713.0	4.8	3.8	0.80
N. PLATTE	541.0	88.0	364.0	4.1	6.1	1.49
TORREJON AB	416.6	74.0	269.0	3.6	5.6	1.55
WASHINGTON	1064.3	124.0	635.0	5.1	8.6	1.68
SACRAMENTO	401.3	53.0	308.0	5.8	7.6	1.30
LOW-LAT						

TAGUAC	2260.6	269.0	1177.0	4.4	8.4	1.92
CLARK AFB	1762.8	122.0	551.0	4.5	14.4	3.20
BALBOA HGHTS	1752.8	166.0	510.0	3.1	10.6	3.44
MADDEN DAM	2240.3	191.0	665.0	3.5	11.7	3.37
GATUN	3035.3	238.0	940.0	3.9	12.8	3.23
CRISTOBAL	3200.4	228.0	895.0	3.9	14.0	3.58
CEYLON	2286.0	112.0	607.0	5.4	20.4	3.77
DJAKARTA	1818.6	135.0	321.0	2.4	13.5	5.67
BOGOR	4229.1	216.0	718.0	3.3	19.6	5.89

Table 8. Daily and hourly annual precipitation data per latitude.

REFERENCES AND BIBLIOGRAPHY

Berthel, Robert 0., and Vernon G. Plank. *Time Durations of Rain Rates Exceeding Specified Thresholds*. Hanscom AFB, Massachusetts: U.S. Air Force Geophysics Laboratory, 1985. AFGL-TR-0122.

Briggs, J. "Estimating the Duration of High-Intensity Rainfall." *The Meteorological Magazine* 97 (1968): 289-293.

Briggs, J., and J.S. Harker. "Estimation of the Duration of Short-Period Rainfall Rates Based on Clock-Hours Values." *The Meteorological Magazine* 98 (1969): 246-252.

Bussey, Howard E. "Microwave Attenuation Statistics Estimated from Rainfall and Water Vapor Statistics." *Proceedings of the Institute of Radio Engineers* 38 (1950): 781-785.

Cobb, L.G. "The Annual and Daily Distribution of Rainfall in Southeast Asia." *Research on Tropical Rainfall Patterns and Associated Mesoscale Systems*, report no. 4. College Station: Texas A&M University, Department of Meteorology (1968). Contract DA-043-AMC-02313(E).

Crane, R.K. "Prediction of Attenuation by Rain." *IEEE Transactions on Communications* COM-28, no. 9 (1980): 1717=1733.

Crane, R.K. "Prediction of the Effects of Rain on Satellite Communication Systems." *Proceedings of the Institute of Electrical and Electronic Engineers, Inc.*(IEEE). 65 (1977): 456-474.

Davis, Allen R., and Daniel J. McMorrow. *Stochastic Models for Deriving Instantaneous Precipitation Rate Distributions*. Air Weather Service. Scott AFB, Illinois: U.S. Air Force Environmental Technical Applications Center (ETAC), 1976. AWS-TR-76-263.

Dutton, E.J., H.T. Dougherty, and R.F. Martin, Jr. *Prediction of European Rainfall and Link Performance Coefficients at 8 to 30 GHz*. Boulder: Institute for Telecommunication Sciences, U.S. Department of Commerce, 1974. AD-AOOO-804.

Fletcher, R.D., and D. Sarlos. *World Record Rainfall and an Envelope of World Record Values*. Air Weather Service (AWS) technical report no. 105-81. Washington, D.C.: AWS, U.S. Air Force, 1951.

Grantham, D.D., et al. "Water Vapor, Precipitation, Clouds and Fog: Chapter 16, 1983 Revision." *Handbook of Geophysics and Space Environments*. Hanscom AFB, Massachsetts: U.S. Air Force Geophysics Laboratory (July 1983). AFGL-TR-83-0181.

Hershfield, D.M. "Estimating the Extreme-Value 1-Minute Rainfall." *Journal of Applied Meteorology* 11 (1972): 936-940.

Hershfield, D.M., L.L. Weiss, and W.T. Wilson. "Synthesis of Rainfall Intensity-Frequency Regimes." *Journal of the Hydraulics Division*, American Society of Civil Engineers (1956): 1041-3 to 1041-4.

Holland, D.J. "The Cardington Rainfall Experiment." *The Meteorological Magazine* 96, no. 1140 (1967): 193-202.

Huschke, R.E., H.H. Bailey, R.S. Nelson, and J.P. Bibbo. *An Improved Weather-Attenuation Model for Earth-Satellite Communication Links*. Contract DAAR 80-80-C-0049. Fort Monmouth, New Jersey: Science Applications, Inc. for the U.S. Army Satellite Communications Agency, 1982.

Jones, Douglas M.A., and Arthur L. Sims. "Climatology of Instantaneous Rainfall Rates." *Journal of Applied Meteorology* 17 (1978): 1135-1140.

Jones, Douglas M.A., and Wayne M. Wedland. "Some Statistics of Instantaneous Precipitations." *Journal of Climate and Applied Meteorology* 23 (1984): 1273-1285.

Lenhard, Robert W., Allen E. Cole, and Norman Sissenwine. *Preliminary Models for Determining Instantaneous Precipitation Intensities from Available Climatology*. L.G. Hanscom Field, Massachusetts: U.S. Air Force Cambridge Research Laboratories, March 1971. AFCRL-71-0168. AD-A722 684.

Lenhard, Robert W., and Norman Sissenwine. *Extremes of 1-, 12-, and 24-Hour Rain for MIL-STD-210B*. L.G. Hanscom Field, Massachusetts, May 1973. U.S. Air Force Cambridge Research Laboratories. AFCRL-TR-73-0329. AD-A766 210.

McMorrow, Daniel J. *A Technique for Estimating Clock Two-Hourly Precipitation Rate Distributions*. Scott AFB, Illinois: U.S. Air Force Environmental Technical Applications Center, May 1978. USAFETAC-TN-78-002. AD-A059 874.

Martin, L.A. "An Investigation of the Rainfall Distribution for Stations in North and Central America." *Research on Tropical Rainfall Patterns and Associated Mesoscale Systems*, report no. 5. College Station: Texas A&M University, Department of Meteorology (May 1964). Contract DA IAO-11001-B-021-09.

Mohr, E.C.J., and F.A. Van Baren. *Tropical Soils*. London: Interscience Publishers, Inc., 1954.

National Energy Authority Thailand. *Hydrologic Data Book* series (1962-1965).

National Oceanic and Atmospheric Administration (NOAA). *Climatological Data Annual Summary*. Asheville, North Carolina: U.S. Department of Commerce, National Climatic Data Center, annual summaries since 1950.

NOAA. *Hourly Precipitation Data Annual Summary*. Asheville, North Carolina: U.S. Department of Commerce, National Climatic Data Center, monthly series.

NOAA. *Monthly Climatic Data for the World*. Sponsored by the World Meteorological Organization. Asheville, North Carolina: U.S. Department of Commerce, National Climatic Data Center, Environmental Data Service monthly series.

Olascoago, M.J. "Some Aspects of Argentina Rainfall." *Tellus* 2 (1950): 312.

O'Reilly, Patrick J. *Clock-Hour/Instantaneous Rainfall Rate Relationships Applicable to the Eastern United States*. Washington, D.C.: U.S. Air Force Environmental Technical Applications Center, 1971. TN 71-12.

Panama Canal Company. *Climatological Data, Canal Zone and Panama*. Annual reports 1957-71. Balboa Heights, Canal Zone: Panama Canal Company.

Rice, P.L., and N.R. Holmberg. "Cumulative Time Statistics of Surface-Point Rainfall Rates." *IEEE Transactions on Communications* COM-21, no. 10 (1973): 1131-1136.

Russak, S.L., and J.W. Easley. "A Practical Method for Estimating Rainfall Rate Frequencies Directly from Climatic Data." *American Meteorological Bulletin* 35, no. 9 (1978): 469-472.

Sternstein,L. *The Rainfall of Thailand*. Bloomington: Indiana University Foundation Research Division, 1962. Contract DA-19-129-QM-1582.

Tattelman, Paul, and D.D. Grantham,"A Survey of Techniques for Determining Short-Duration Precipitation Rate Statistics." *Air Force Surveys in Geophysics*. Hanscom AFB, Massachusetts: U.S. Air Force Geophysics Laboratory (1982). AFGL-TR-82-0357.

Tattelman, Paul, and K. Scharr. "A Model for Estimating 1-Minute Rainfall Rates." *Journal of Climate and Applied Meteorology* 22 (1983): 1575-1580.

U.S. Air Force Environmental Technical Applications Center (ETAC). *Precipitation Attenuation at 8 Kmc: Final Estimate*. Washington, D.C.: ETAC, 1962.

U.S. Air Force Environmental Technical Applications Center (ETAC). *Precipitation Rate Relationships*, report no. 5785. Washington, D.C.: ETAC, July 1967.

U.S. Army Engineer Division, North Pacific. *Mekong Systems Analysis Project*. Portland, Oregon: U.S. Army Engineer Div., North Pacific, 1968.

U.S. Army Materiel Command. "Natural Environmental Factors." *Engineering Design Handbook*, Environmental Series, part 2, ch. 7, 'Rain.' AMCP-706-116. Alexandria, Virginia: Army Materiel Command (1975). AD-A012-648.

U.S. Weather Bureau. *Rainfall Intensity Duration-Frequency Curves for Selected Stations in the United States, Alaska, Hawaiian Islands, and Puerto Rico*, technical paper no. 25. Washington, D.C.: U.S. Government Printing Office, Superintendent of Documents, 1955.

Wexler, Ruth L. "The Relationship between Daily and Annual Rainfall in Thailand." *Proceedings of the Technical Exchange Conference*, Air Weather Service technical report 196 (1967): 226-242.

Winner, Donald C. *Climatological Estimates of Clock-Hour Rainfall Rates*. Air Weather Service. Washington, D.C.: U.S. Air Force Environmental Technical Applications Center (ETAC), 1968. AWS-TR-68-202.

World Meteorological Organization. "Manual for Estimation of Probable Maximum Precipitation." *Operational Hydrology*, report no. 1, WMO 332. Geneva: World Meteorological Organization (1973).

APPENDIX A

Sample Problems

This section provides sample problems and their solutions by means of equations (1a) to (1c) and/or figures 1 and 2.

1) Objective: to find the frequency in days (d) per year with rain-rate, r, >35 mm/day.

Station = Chanthaburi, Thailand

$P = 3305$ mm (annual rainfall)

$D = 171$ days of rain per year

$r = 35$

$S = 35/(P/D) = 1.81$

$x = 21.0(S) = 38.0$

$y = 3.6 + 21(\ln 38) = 80.0$

$d = D(100-y)/100 = 34$

34 days Ans.

(observed = 29 days)

Alternate method by figure 2

For $S = 1.81$, read $(100-y) = 20$

$d = 171(20/100)$

or $d = 34$

2) Objective: to find the percent hours per year that a rain rate of 0.1 inch per hour is equalled or exceeded.

Station = Ceylon, India

P = 90 inches (annual rainfall)

H = 607 hours per year of rain

F = 8760 total hours in a year

r = 0.1 inch/hr

$S = r/(P/H) = .67$

$x = 21(S) = 14.1$

$y = 3.6 + 21(\ln x) = 59$

$h = H(100-y)/100 = 249$ hours

$f = 100(h/F) = 2.8$ 2.8% Ans.

(observed = 2.7%)

3) Objective: to find a rain rate, r, that is equalled or exceeded 2% hours per year.

Station = Washington, D. C.

P = 41.9 inches (annual rainfall)

H = 635 hours of rain per year

h = 175.2 = 2% hours per year

$y' = 100(h/H) = 27.6\%$ of the rain hours

$y = 100-y' = 72.4$

x = 26 (read from figure 1)

$S = x/21 = 1.24$

$r = S(P/H) = .084$ inch/hr .084 inch/hr Ans.

(observed = .076 inches/hr)

4) **Objective:** to find the percent frequency (f) of days (d) per year with a rain rate between 35 and 10 mm/day.

Station = Mae Hong Son, Thailand

P = 1255 mm (annual rainfall)

D = 112 days per year

r′ = 35

r = 10

S′ = r′/(P/D) = 3.12

y′ = 90 (read y at S = 3.12 on figure 2)

S = r/(P/D) = .89

y = 64.5 (read y at S = .89 on figure 2)

d = (y′-y)(D/100) = **28.6 days**

f = 100(28.6/365) = **7.82% days/year**

7.82% Ans.

(observed = 8.5%)

5) **Objective:** To estimate maximum daily rainfall

Station = Sakon Nakhon, Thailand (Sept 1964)

P = 262.7 mm (monthly rainfall)

D = 20 days per month

f = 100/D = 5% (1 day of rain)

y = 95

S = 3.7 (at y = 95 on figure 2)

r = S(P/D) = 48.6

48.6 mm Ans.

(observed = 47.9 mm)

APPENDIX B

Additional/Alternate Formulas

1) Explanation

Since neither model is a perfect fit and since rainfall never reproduces itself exactly, the equations given at best provide a guide to common trends noted in long-term or even single sets of observations of daily, hourly or instantaneous rainfall, respectively. Usually, no single equation is applicable to the entire distribution, but for the most part either the general or explicit model will recover rain rates up to about the 95th frequency percentile.

To the extent possible, the equations employed have a coefficient of determination of $r^2 > .90$ ($r^2 = 1.0$ represents a perfect fit, $r^2 = 0$ is no fit). All equations are subject to revision as data improve.

Discrepancies in the constants come about if, for any given formula and data set, a difference obtains in the frequency range (y) selected. The observations themselves, as figures 4 and 5 or tables 4, 5, 6b, 6c, or 7b provide the most reliable information concerning the frequency of short-term rainfall. The formulas are sensitive to the size of the class frequencies utilized.

2) Equations for x vs y

where y = cumulative percent frequency

x = cumulative percent amount

and A,B,a,b are constants

a) Equation (1): $y = A + B(\ln x)$

Table B1 lists constants A and B for the curves in figure 3 of the general model.

Of the distributions in figure 3, curve No. 3 (same as figure 1) is referred to as the universal or default distribution.

For instantaneous rainfall, from a set of depth-duration plots for one-hour storms of 50 mm to 127mm total amounts (U.S. Weather Bureau), equations of the above format have been determined, namely,

$$\text{50 mm:} \quad y = -35.1 + 28.9(\ln x) \qquad \text{(B1)}$$

$$\text{127 mm:} \quad y = -69.7 + 35.8(\ln x) \qquad \text{(B2)}$$

Once a set of equations, as (B1) and (B2) has been obtained for two or more cases of specified hourly rainfall, then the constants, A or B, for any intermediate rainfall may be readily derived as functions of P/H or P/M. For P/M, from 0.85 mm/min to 2.12 mm/min (corresponding to 50 mm/hr and 127 mm/hr, respectively), A and B may be found as follows

$$A = -12 - 27.2(P/M) \qquad \text{(B3)}$$

$$B = 24.3 + 5.5(P/M) \qquad \text{(B4)}$$

$$P/M = \text{mm/min}$$

b) For equation (2): $x = a \exp(by)$

$$50 \text{ mm:} \quad x = 3.42 \exp(.03\, y) \qquad \text{(B5)}$$

$$127 \text{ mm:} \quad x = 7.14 \exp(.03\, y) \qquad \text{(B6)}$$

c) For equation (3): $y = a\, x^b$

$$50 \text{ mm:} \quad y = 7.51\, x^{.60} \qquad \text{(B7)}$$

$$127 \text{ mm:} \quad y = 3.57\, x^{.76} \qquad \text{(B8)}$$

3) Equations for y vs R

where y = the same as above

R = rain rate (in specified units)

a) For equation (4): $y = A + B(\ln R)$

For daily rain, 8.2 mm/day to 17.0 mm/day, the derivation formulas for the constants A and B are

$$A = 38.8 - 1.8(P/D) \qquad \text{(B9)}$$

$$B = 21 \qquad \text{(B10)}$$

For hourly rain, 2.8 mm/hr to 4.5 mm/hr (data from various sources), the derivation formulas for the constants A and B are

$$A = 64.7 - 6.6(P/H) \quad (r = .8) \qquad \text{(B11)}$$

$$B = 21.7 \qquad \text{(B12)}$$

b) For equation (5): $y = a\, R^b$

	a	b
For $y > 70$	56.4	0.20
For R values (mm/hr)		
12.7 - 25.4	74.4	0.09

CURVE #	A	B
1	30.7	16.5
2	16.1	19.0
3	3.6	21.0
4	-15.8	25.0
5	-37.2	29.7
6	-69.0	36.2
7	-107.0	44.0

Table B1. Constants for equation (1) for curves in figure 3.

APPENDIX C

Computer Programs

The distribution in figure 1 (general format) is utilized as the default or universal model for the first five programs. However, programs No.4 and No.5 also include the explicit model, which employs equations (4) and (5). The required constants, A and B, may be assigned if they are available for the rainfall regime in question, that is, the particular P/D, or P/H. Otherwise, they may be derived, as explained previously.

If any rainfall regime being investigated has a value of P/D or P/H within the limits of those given in figures 4 or 5 or tables 4 to 7, very often reasonable estimates in terms of percentiles may be made by inspection for comparison with computer results.

1) DAYRATE

```
1 REM "DAYRATE"  RLW 86
2 LPRINT
3 PRINT" PROGRAM TO EST DAILY RAIN RATE PROBABILITIES"
4 REM EQUATION:  Y = 3.6 + 21 LOG (X)     NOTE LOG = NAT LOG
6 REM DX/DY = X/21   LET S = DX/DY
7 REM THE RAIN RATE, R, AT ANY Y IS R=S*(P/D)
8 LPRINT"STATION","INTERVAL"," P(MM)  ";"    D    ";" RATE(R)";" DAYS>R"
9 LPRINT
10 PRINT"ENTER STATION"
12 INPUT S$
20 PRINT "YEAR, SEASON, OR MONTH? IF SEASON, WHICH? IF MONTH, WHICH?"
22 INPUT I$
30 PRINT "ENTER TOTAL RAIN IN MILLIMETERS"
35 INPUT P
70 PRINT " NUMBER OF RAIN DAYS"
80 INPUT D
82 A = 3.6
84 B = 21
85 I = P/D
90 PRINT "ENTER RAIN RATE IN MM"
100 INPUT R
130 S = R/I
140 X = S * B
150 Y = A + (B*LOG(X))
152 IF Y<0 THEN Y = 0:GOTO 160
154 IF Y>100 THEN Y = 100
160 F =(100-Y)*D/100
164 IF Y>100 THEN F = 0
170 LPRINT S$,
171 LPRINT I$,
172 LPRINT USING"####.#  ";P,D,R,F
180 PRINT"ANOTHER CASE? Y? N?"
182 INPUT A$
184 IF A$="Y" THEN GOTO 10
190 END
```

SAMPLE OUTPUT: DAYRATE

STATION	INTERVAL	P(MM)	D	RATE(R)	DAYS>R
WASH.D.C.	AUTUMN	203.2	24.0	6.4	9.2
HILO	SPRING	617.2	70.8	12.7	17.4
BERLIN	YEAR	584.2	171.0	1.0	99.6
CHANTHABURI	YEAR	3304.5	170.7	10.0	79.1

2) HOURRATE

```
2 REM "HOURRATE" IN/HR RLW 86
4 REM TO DET NO. HOURS WITH RAIN>=.05, .10, .25 INCHES
6 OPTION BASE 1
8 DIM F(3), R(3)
10 LPRINT
11 LPRINT
12 LPRINT""TAB(30)"NO. HOURS > IN/HR GIVEN"
14 LPRINT
16 R(1) =.05
18 R(2) =9.999999E-02
20 R(3) =.25
22 LPRINT"STATION"," P(IN)   ";"    H    ";"    .05   ";
23 LPRINT"    .10    ";"    .25   "
24 LPRINT
30 PRINT"ENTER STATION"
32 INPUT S$
34 PRINT "ENTER TOTAL RAIN IN INCHES"
36 INPUT P
38 PRINT "ENTER TOTAL HOURS OF RAIN"
40 INPUT H
42 I = P/H
44 FOR L = 1 TO 3
50 S = R(L)/I
52 X = S*21
54 Y = 3.6+21*(LOG(X))
60 IF (Y<0) THEN Y=0 : GOTO 70
62 IF(Y>100) THEN Y=100
70 F(L) = (100-Y)*H/100
72 NEXT L
80 LPRINT S$,
90 LPRINT USING"####.#   ";P, H, F(1),F(2),F(3)
100 PRINT"ANOTHER CASE?"
110 INPUT A$
120 IF A$="Y" THEN GOTO 30
130 END
```

SAMPLE OUTPUT: HOURRATE

			NO. HOURS > IN/HR GIVEN		
STATION	P(IN)	H	.05	.10	.25
TOWNSVILLE	45.7	364.0	188.5	135.6	65.5
PESHAWAR	14.7	109.0	58.1	42.2	21.3
WASHINGTON	41.9	635.0	243.1	150.7	28.5
KRAKOR	50.9	388.0	204.6	148.1	73.4

3) FREQHOUR

```
2 REM "FREQHOUR " RLW 86
3 REM THIS IS AN INTERACTIVE PROGRAM
4 REM TO FIND RAIN RATE EQUALLED OR EXCEEDED
6 REM THE % HOURS/YEAR INDICATED
8 REM TOTAL HOURS PER YEAR = 8760; 1% OF TIME = 87.6 HOURS
10 REM PARAMETERS REQUIRED: P = TOTAL ANNUAL RAIN, H = HOURS OF RAIN
12 DATA 0.1, 0.2, 0.5, 1.0, 2.0
14 DIM R(5), F(5), C(5), Y(5)
16 FOR L = 1 TO 5
18 READ C(L)
20 F(L) = C(L) * 87.6
22 NEXT L
24 LPRINT
26 LPRINT" "TAB(38)"RAIN RATE(MM/HR) EQUALLED OR EXCEEDED"
27 LPRINT" "TAB(38)"       % HOURS INDICATED"
28 LPRINT
30 LPRINT"STATION","     P     ";"     H     ";
32 LPRINT"   .1%   ";"   .2%   ";"   .5%   ";"    1%   ";"    2%   "
34 LPRINT
40 A = 3.6
42 B = 21
44 PRINT"ENTER STATION"
46 INPUT S$
50 PRINT"ENTER TOTAL ANNUAL RAIN IN MILLIMETERS"
52 INPUT P
54 PRINT"ENTER NUMBER OF HOURS OF RAIN PER YEAR"
56 INPUT H
60 FOR L = 1 TO 5
62 Y1 = F(L)*100 /H
64 Y = 100 -Y1
66 Z = (Y-A)/B
68 X = EXP(Z)
70 R(L) = (X/B)*(P/H)
72 NEXT L
80 LPRINT S$,
82 LPRINT USING"#####.#   "; P,H,
84 LPRINT USING"####.#   ";R(1),R(2),R(3),R(4),R(5)
90 PRINT"ANOTHER CASE? Y? N?"
92 INPUT A$
94 IF (A$ = "N") THEN GOTO 100
96 GOTO 44
100 END
```

SAMPLE OUTPUT: FREQHOUR

			RAIN RATE(MM/HR) EQUALLED OR EXCEEDED % HOURS INDICATED				
STATION	P	H	.1%	.2%	.5%	1%	2%
THULE	139.7	211.0	2.5	2.1	1.2	0.4	0.1
PARIS	569.0	713.0	3.5	3.3	2.8	2.1	1.2
N.PLATTE	541.0	364.0	6.2	5.5	3.9	2.2	0.7
WASH.D.C.	1064.3	635.0	7.4	6.9	5.7	4.1	2.1
GUAM	2260.6	1177.0	8.7	8.4	7.5	6.3	4.4
CEYLON	2286.0	607.0	16.5	15.4	12.5	8.9	4.5

OBS RAIN RATE(MM/HR) EQUALLED OR EXCEEDED
% HOURS/YEAR INDICATED

STATION	P	N	.1%	.2%	.5%	1%	2%
THULE	139.7	211.0	1.9	1.3	0.8	0.5	0.3
PARIS	569.0	713.0	6.0	3.9	2.6	1.7	1.1
N.PLATTE	541.0	364.0	6.6	5.1	3.1	1.5	0.7
WASH.D.C.	1064.3	635.0	12.0	7.2	5.1	3.5	1.7
GUAM	2260.6	1177.0	14.0	12.0	8.0	6.2	4.4
CEYLON	2286.0	607.0	28.0	20.0	13.0	7.4	3.7

4) TESTDAY

```
2 REM"TESTDAY" MM/DAY BY R.L.WEXLER NOV 85
4 OPTION BASE 1
6 DATA 6.35, 12.70, 25.4
8 DATA 3.6, 21.0
10 DATA PENSACOLA-WI,297.9, 30.2
12 DATA 12.8, 8.0, 3.0
13 DIM Y0(5), Y(5), Y1(5)
14 DIM F0(5),F(5),F1(5)
17 FOR L = 1 TO 3
18 READ R(L)
20 NEXT L
22 READ A,B
24 READ S$, P, D
25 I = P/D
26 FOR L = 1 TO 3
28 READ F0(L)
30 NEXT L
31 LPRINT
32 LPRINT"TABLE    EXPLICIT VS GENERAL MODEL: DAILY RAIN"
33 LPRINT
34 LPRINT S$;": P =";
35 LPRINT USING"#####.#";P;
36 LPRINT" MM   D =";
37 LPRINT USING"####.#";D;
38 LPRINT"   P/D =";
39 LPRINT USING "###.##";I
40 LPRINT
42 LPRINT" "," NO. DAYS WITH RAIN > RATE GIVEN"
43 LPRINT
44 LPRINT"MM/DAY","  OBS"," EST-X"," EST-G"
45 LPRINT
46 A1 = 38.8- 1.8 * I
48 B1 = 21
50 FOR L = 1 TO 3
51 Z1 =LOG(R(L))
52 Y1(L) = A1 + B1*Z1
53 IF Y1(L)<0 THEN Y1(L) =0: GOTO 56
54 IF Y1(L)>100 THEN Y1(L) =100
55 F1(L) = (100-Y1(L))*D/100
56 NEXT L
58 FOR L = 1 TO 3
60 S = R(L)/I
61 X = S*P
62 Y(L) = A + B * (LOG(X))
63 IF Y(L)<0 THEN Y(L) =0: GOTO 68
64 IF Y(L)>100 THEN Y(L) =100
66 F(L) = (100-Y(L))* D/100
68 NEXT L
```

```
70 FOR L = 1 TO 3
72 LPRINT USING"####.##       ";R(L),
74 LPRINT USING"####.#        ";FO(L),F1(L), F(L)
76 NEXT L
78 LPRINT
90 FOR L = 1 TO 3
92 YO(L) =(D-FO(L))*100/D
94 NEXT L
98 LPRINT
100 LPRINT " "TAB(26)"CUM % RAIN DAYS"
101 LPRINT
102 FOR L = 1 TO 3
103 LPRINT USING"####.##       ";R(L),
104 LPRINT USING"####.#        ";YO(L), Y1(L), Y(L)
108 NEXT L
110 LPRINT
114 LPRINT"  A      B"
116 LPRINT USING"##.#     ";A1,B1
120 END
```

SAMPLE OUTPUT: TESTDAY

EXPLICIT VS GENERAL MODEL: DAILY RAIN

a. PENSACOLA-WI: P = 297.9 MM   D = 30.2   P/D = 9.86

NO. DAYS WITH RAIN > RATE GIVEN

MM/DAY	OBS	EST-X	EST-G
6.35	12.8	12.1	12.6
12.70	8.0	7.7	8.2
25.40	3.0	3.3	3.8

CUM % RAIN DAYS

6.35	57.6	59.9	58.3
12.70	73.5	74.4	72.8
25.40	90.1	89.0	87.4

A1	B1
21.0	21.0

SAMPLE OUTPUT: TESTDAY

EXPLICIT VS GENERAL MODEL: DAILY RAIN

b. SAN JUAN-YR: P = 1499.9 MM D = 199.2 P/D = 7.53

NO. DAYS WITH RAIN > RATE GIVEN

MM/DAY	OBS	EST-X	EST-G
6.35	64.8	71.6	71.8
12.70	34.0	42.6	42.8
25.40	15.0	13.6	13.8

CUM % RAIN DAYS

6.35	67.5	64.1	64.0
12.70	82.9	78.6	78.5
25.40	92.5	93.2	93.1

A1	B1
25.2	21.0

c. WASH.D.C.-SU: P = 316.7 MM D = 29.2 P/D = 10.85

NO. DAYS WITH RAIN > RATE GIVEN

MM/DAY	OBS	EST-X	EST-G
6.35	12.8	12.2	12.8
12.70	8.0	8.0	8.5
25.40	3.0	3.7	4.3

CUM % RAIN DAYS

6.35	56.2	58.1	56.3
12.70	72.6	72.7	70.8
25.40	89.7	87.2	85.4

A1	B1
19.3	21.0

5)TESTHOUR

```
1 REM "TESTHOUR" MM/HR RLW JAN 30 86
2 LPRINT"SAMPLE OUTPUT: TESTHOUR"
3 LPRINT
4 REM P/N 2.8 -4.5 MM/HR: A=64.7-6.6(P/N), B=22
6 DATA 1.27,2.54,5.08,6.35,12.70
10 DATA PESHAWAR,373.4, 109
12 DATA 59.5, 39.3, 25.0, 19.4, 5.8
13 DIM Y(5),Y1(5), Y2(5)
14 DIM R(5), A(3),B(3), F(5),F1(5),F2(5)
17 FOR L = 1 TO 5
18 READ R(L)
20 NEXT L
21 READ S$, P, N
22 I = P/N
23 A(1) = 64.7-6.6 * (P/N)
24 B(1) = 22
26 FOR L = 1 TO 5
28 READ F(L)
29 Y(L) = (N- F(L))*100/N
30 NEXT L
32 LPRINT"EXPLICIT MODEL (X) VS GENERAL MODEL (G): HOURLY RAIN"
33 LPRINT
34 LPRINT S$;": P =";
35 LPRINT USING"#####.#";P;
36 LPRINT" MM   N =";
37 LPRINT USING"#####";N;
38 LPRINT"   P/N =";
39 LPRINT USING "###.##";I
40 LPRINT
42 LPRINT" ","NO. HOURS WITH RAIN > RAIN-RATE GIVEN"
43 LPRINT
44 LPRINT"MM/HR", "  OBS",  " EST-X"," EST-G"
45 LPRINT
46 A(2) = 3.6
47 B(2) = 21
48 A(3)=56.4
49 B(3) = .2
50 FOR L = 1 TO 5
52 Y1(L) = A(1) + B(1) * (LOG(R(L)))
53 IF Y1(L)>70 THEN Y1(L) = A(3)*R(L)^B(3)
54 IF Y1(L)>100 THEN Y1(L) =100
55 F1(L) =(100-Y1(L))*N/100
56 NEXT L
58 FOR L = 1 TO 5
60 S = R(L)/I
62 X = S * B(2)
64 Y2(L) = A(2) + B(2) * (LOG(X))
65 IF Y2(L)>100 THEN Y2(L)=100
66 F2(L) = (100 - Y2(L)) * N/100
68 NEXT L
```

```
70 FOR L = 1 TO 5
72 LPRINT USING"####.##        ";R(L),
74 LPRINT USING"####.#         ";F(L),F1(L),F2(L)
76 NEXT L
78 LPRINT
90 LPRINT " "," ","CUM % FREQ"
92 LPRINT
93 FOR L = 1 TO 5
94 LPRINT USING"####.##        ";R(L),
96 LPRINT USING"####.#         ";Y(L),Y1(L),Y2(L)
98 NEXT L
100 LPRINT
102 LPRINT "  A       B       a       b"
104 LPRINT USING"##.##   ";A(1),B(1),A(3),B(3)
106 LPRINT"A,B for Equation (4), a,b for Equation (5)"
110 END
```

SAMPLE OUTPUT: TESTHOUR

EXPLICIT MODEL (X) VS GENERAL MODEL (G): HOURLY RAIN

a) TOWNSVILLE: P = 1160.8 MM   N = 364   P/N = 3.19

NO. HOURS WITH RAIN > RAIN-RATE GIVEN

MM/HR	OBS	EST-X	EST-G
1.27	189.0	186.0	188.6
2.54	116.0	130.5	135.6
5.08	66.0	79.8	82.6
6.35	51.1	66.9	65.5
12.70	19.0	22.7	12.5

CUM % FREQ

1.27	48.1	48.9	48.2
2.54	68.1	64.2	62.8
5.08	81.9	78.1	77.3
6.35	86.0	81.6	82.0
12.70	94.8	93.8	96.6

A	B	a	b
43.65	22.00	56.40	0.20

A,B for Equation (4), a,b for Equation (5)

b) PESHAWAR: P = 373.4 MM   N = 109   P/N = 3.43

NO. HOURS WITH RAIN > RAIN-RATE GIVEN

MM/HR	OBS	EST-X	EST-G
1.27	59.5	57.4	58.1
2.54	39.3	40.8	42.2
5.08	25.0	23.9	26.4
6.35	19.4	20.0	21.3
12.70	5.8	6.8	5.4

CUM % FREQ

1.27	45.4	47.3	46.7
2.54	63.9	62.6	61.3
5.08	77.1	78.1	75.8
6.35	82.2	81.6	80.5
12.70	94.7	93.8	95.1

A	B	a	b
42.09	22.00	56.40	0.20

A,B for Equation (4), a,b for Equation (5)

6) INSTANT

```
2 REM "INSTANT" MM/MIN  R. L. WEXLER 6 DEC 85
4 OPTION BASE 1
5 REM DATA FROM USWB
6 REM TO EST THE DECILES FOR MAX-DEPTH 1-HR STORMS
8 REM 50.8 MM (2 INCHES) AND 127 5 INCHES)
10 REM EQUATION Y = A + B LN X,  X= S*B, R = S(P/M)
14 DIM Y(10), R(2), A(2), B(2), P(2),I(2)
20 LPRINT
22 LPRINT " RAIN RATE DECILES FOR MAX 1-HR STORMS"
24 LPRINT
26 LPRINT" ","          MM/MIN"
32 LPRINT"CUM % FREQ","  0.85","  2.12"
34 LPRINT
40 A(1) = -35.1
42 B(1) = 28.9
44 A(2) = -69.7
46 B(2) = 35.8
48 P(1) =50.8
50 P(2) = 127
52 I(1) =P(1)/60
54 I(2) = P(2)/60
58 FOR L = 1 TO 9
60 Y(L) = 10 * L
62 FOR N = 1 TO 2
64 Z = (Y(L)-A(N))/B(N)
66 X = EXP(Z)
68 S = X/B(N)
70 R(N) = S * I(N)
72 NEXT N
80 LPRINT USING"####          ";Y(L);
82 LPRINT USING"###.##        ";R(1), R(2)
90 NEXT L
92 REM IF R = P/M, X = B
93 Y1 = -35.1 + 28.9 * (LOG(28.9))
94 Y2 = -69.7 + 35.8 * (LOG(35.8))
95 Y1 = 100 -Y1
96 Y2 = 100 -Y2
98 LPRINT
99 LPRINT
110 LPRINT "% FREQ > P/M",
112 LPRINT USING"###.#         ";Y1, Y2
120 END
```

SAMPLE OUTPUT: INSTANT

RAIN RATE DECILES FOR MAX 1-HR STORMS

	MM/MIN	
CUM % FREQ	0.85	2.12
10	0.14	0.55
20	0.20	0.72
30	0.28	0.96
40	0.39	1.27
50	0.56	1.67
60	0.79	2.21
70	1.11	2.93
80	1.57	3.87
90	2.22	5.12
% FREQ > P/M	37.9	41.6

7) ONE-HOUR

```
1 REM "MM/MIN" CHANGED TO "ONE-HOUR"
2 REM "ONE-HOUR" RLW 86
3 REM DATA FROM CANAL ZONE AND PANAMA
4 OPTION BASE 1
18 DIM Y(10), R(10), A(10),B(10), P(10), I(10)
20 LPRINT
22 LPRINT "ONE-HOUR EXCESSIVE RAIN: CANAL ZONE AND PANAMA"
24 LPRINT
28 LPRINT" "TAB(28)" RAIN RATE (MM/HR)"
30 LPRINT
32 LPRINT"CUM % FREQ",
34 LPRINT"  25.4","  50.8", "  76.2"," 101.6"," 127.0"
36 LPRINT
38 DATA 15,20, 25, 30, 35, 40, 45, 50, 55, 60
39 DATA 1,2,3,4,5
40 FOR L = 1 TO 10
41 READ Y(L)
42 Y(L)=Y(L)*(100/60)
44 NEXT L
46 FOR N = 1 TO 5
48 READ P(N)
49 P(N) =P(N)*25.4
54 I(N) = P(N)
56 A(N) = -11.5 - 1.15 * I(N)
58 B(N) = 25.3 + .23 * I(N)
60 NEXT N
62 FOR L = 1 TO 10
63 FOR N = 1 TO 5
64 Z = (Y(L)-A(N))/B(N)
66 X = EXP(Z)
68 S = X/B(N)
70 R(N) = S * I(N)
72 NEXT N
80 LPRINT USING"####.#        ";Y(L);
82 LPRINT USING"####.#        ";R(1),R(2),R(3),R(4),R(5)
90 NEXT L
92 LPRINT
94 LPRINT
96 LPRINT
97 LPRINT "EQUATION (1)"
98 LPRINT "  A",
100 LPRINT USING"####.#        ";A(1), A(2), A(3), A(4), A(5)
102 LPRINT "  B",
104 LPRINT USING"####.#        ";B(1),B(2),B(3),B(4),B(5)
110 END
```

SAMPLE OUTPUT: ONE-HOUR

ONE-HOUR EXCESSIVE RAIN: CANAL ZONE AND PANAMA

	RAIN RATE (MM/HR)				
CUM % FREQ	25.4	50.8	76.2	101.6	127.0
25.0	6.7	17.9	32.3	48.8	66.3
33.3	8.8	22.4	39.2	57.9	77.3
41.7	11.5	28.1	47.6	68.7	90.1
50.0	15.0	35.2	57.9	81.5	104.9
58.3	19.6	44.0	70.3	96.7	122.3
66.7	25.6	55.2	85.4	114.8	142.5
75.0	33.5	69.1	103.8	136.2	166.0
83.3	43.8	86.6	126.1	161.6	193.4
91.7	57.2	108.5	153.1	191.8	225.4
100.0	74.8	135.9	186.0	227.7	262.6
EQUATION (1)					
A	-40.7	-69.9	-99.1	-128.3	-157.5
B	31.1	37.0	42.8	48.7	54.5

END

FILMED

11-89

DTIC